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GEOLOGICAL SURVEY BULLETIN 996-D

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By GORDON A. MACDONALD *and* CHESTER K. WENTWORTH

A CONTRIBUTION TO GENERAL GEOLOGY

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A report of the Hawaiian Volcano Observatory

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ABSTRACT

The year 1951 produced no eruptive activity of the Hawaiian volcanoes, but much subsurface volcanic uneasiness was manifested in tilting of the ground surface and abundant earthquakes. Records of the earthquakes, of magnetic changes, of changes in the width of cracks, and of tilting of the ground surface, all reveal some of the changes that took place.

In December 1950, rapid south-southwestward tilting of the ground at the northeastern rim of Kilauea caldera indicated a sinking of the top of Kilauea volcano, in response to a decrease of pressure beneath. Throughout the first quarter of 1951 Kilauea was quiet, but in April there began a period of marked uneasiness. This was evidenced by a strong earthquake originating on the east rift zone on April 22, followed by 108 aftershocks, and on April 24 by the beginning of rapid northward tilting at the northeastern rim of the caldera, apparently accompanying an increase of volcanic pressure at depth. The increase of pressure beneath Kilauea continued until early August.

On August 21 the uneasiness was abruptly transferred to Mauna Loa. The earthquake at 00^h57^m on August 21, in Kona, on the western slope of Mauna Loa, was the most severe of any on the island of Hawaii since 1868. In its epicentral area, in the vicinity of Napoopoo and Captain Cook in central Kona, it had an intensity of 7 on the modified Mercalli scale. The earthquake was felt generally and strongly over the island of Hawaii, and weakly by many people in Honolulu, 200 miles away. The Kona seismograph was severely damaged by the first shock, and was only restored to operation 2 days later. The seismographs at the western rim of Kilauea caldera, and on the southeastern slope of Mauna Loa, at an altitude of 6,700 feet, were dismantled by the first waves and provided no useful records of the main earthquake. The seismograph at the northeastern rim of Kilauea caldera recorded the preliminary waves of the quake, but was dismantled by the first surface waves. All the instruments were restored to operation as soon as possible after the main quake, and recorded more than 1,000 aftershocks through the next few weeks.

Damage to structures and roads in the Kona district was severe and extensive. Several churches and houses and about 150 water tanks were demolished. Many houses suffered lesser damage. In every cemetery for a distance of 25 miles there was some derangement of headstones, and in those cemeteries near the epicenter damage was severe. Many stone walls were thrown down.

A study of the instrumental records and the distribution of damage indicate that the epicenter of the earthquake was probably on the Kealakekua fault

beneath the ocean, about 4 miles west of Napoopoo. The submarine origin of the quake is confirmed by the generation of a small tsunami.

During September a group of earthquakes originated on the Kaoiki fault zone, between Mauna Loa and Kilauea. In October earthquakes originated beneath the summit area of Mauna Loa and along both rift zones, as well as on the Kaoiki fault, and on the Kealakekua fault in Kona. On November 8 a strong quake originated on the southwest rift of Mauna Loa near Kahuku Ranch headquarters, and throughout November earthquakes came from scattered sources in Mauna Loa and Kilauea. The uneasiness of both volcanoes continued into early December, but the year closed with relative quiet prevailing.

In view of subsequent developments, there is little doubt that the general uneasiness throughout most of the year resulted from an increase of volcanic pressure beneath both volcanoes, which led eventually to the eruption of Kilauea on June 27, 1952.

INTRODUCTION

The offices and shop of the Hawaiian Volcano Observatory occupy a building at Uwekahuna, on the western rim of Kilauea caldera near the highest point of Kilauea mountain. In addition the Observatory operates five seismograph stations and two independent tilt stations on the island of Hawaii. The master station for earthquake recording and tilt measurement is the Whitney Laboratory of Seismology, located on the northeastern rim of Kilauea caldera beneath the western end of the Volcano House, at the original site of the Hawaiian Volcano Observatory (fig. 31). The Uwekahuna station, near the western rim of Kilauea caldera about a quarter of a mile west of the main Observatory building (fig. 31), contains seismographs and tiltmeters.

The Mauna Loa station lies on the southeastern slope of Mauna Loa at an altitude of 6,700 feet, 8 miles northwest of the Observatory (fig. 31). Tilt is measured from the records of the Hawaiian-type seismograph at the Mauna Loa station, but the record has proved of little use. Other seismograph stations are located in Hilo, 23 miles northeast, and in Kealakekua, Kona, 43 miles N. 80° W., of the Observatory (fig. 41). Tilt is not measured at the Hilo and Kona stations. Two tilt-measuring stations are located on the floor of Kilauea caldera, respectively southeast and west of Halemaumau crater (fig. 35).

Accounts of the activity of the Hawaiian Volcano Observatory from the time it was taken over by the Geological Survey in December 1947, until the end of the year 1950 have already been published (Finch and Macdonald, 1951; Finch and Macdonald, 1953). The present report continues the account of Observatory activities through the year 1951.

The principal change in the organization during the year was the retirement on February 28 of Ruy H. Finch as volcanologist in charge of the Observatory. He was succeeded by Gordon A. Macdonald. In May, Chester K. Wentworth retired as geologist for the Honolulu Board of Water Supply and assumed full-time duties as geologist for the Observatory. He returned to part-time status in October. John C. Forbes served as instrumentmaker, and LaVieve G.

Forbes served as part-time clerk-stenographer throughout the year. During July, Brother Bernard T. Pleimann was succeeded by Sister M. Thecla as operator of the seismograph station at St. Joseph's School in Hilo.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the aid of many persons on the island of Hawaii in the routine operations of the Hawaiian Volcano Observatory and during the course of special investigations. Although our sincere thanks are extended to all, it is impossible to mention all by name.

The staff of Hawaii National Park has been constantly helpful and we wish to express our appreciation to F. R. Oberhansley, superintendent, for innumerable courtesies and assistance in many ways. D. H. Hubbard, naturalist, and V. R. Bender, biologist, have supplied information on several occasions. E. K. Field, chief ranger, and E. L. Bohlin, ranger, made aerial photographs of parts of the caldera of Kilauea and the southwest rift zone of Mauna Loa, for use by the Observatory in mapping.

Mrs. Alfred E. Hansen of Naalehu, Miss Nancy Wallace of Kealakekua, Robert M. Baldwin of Hilo, Edward G. Wingate of Kapoho, and Allen P. Johnston, manager of the Kapapala Ranch, have all aided greatly by reporting to the Observatory the time and character of earthquakes felt by them and others in their districts.

Copies of the seismograms of the major earthquake of August 21 recorded at the Honolulu Magnetic Observatory of the U. S. Coast and Geodetic Survey, at Barbers Point on Oahu, were kindly loaned to us by Roland E. White, the observer in charge. Commander C. A. George of the Coast and Geodetic Survey, also kindly supplied us with copies of the tide-gage records from Honolulu and Hilo harbors, showing the small tsunami that followed the earthquake.

Many persons cooperated in supplying information on water tanks damaged by the earthquake of August 21. Especially helpful were: John Iwane, of the Extension Service, University of Hawaii; Masuoka Nagai, of Captain Cook Coffee Co.; Mark Sutherland, principal of Konawaena School; and George T. Imai, of the Hawaii County Road Department; and the Hilo office of the Territorial Department of Public Instruction. The Territorial Board of Health supplied data on the location and ownership of cemeteries in Kona. Homer A. Hayes has aided by supplying information on damage by the August 21 earthquake, and data on the age of several of the old churches in the Kona district.

SEISMOGRAPHS AND TILTMETERS

An account of the seismographs and tiltmeters in operation by the Hawaiian Volcano Observatory at the close of 1949 was given in an

earlier report (Finch and Macdonald, 1951). For the most part the installations remained the same through 1950–51. Some minor changes are described below.

In September 1950, a Sprengnether vertical seismograph was installed in the Uwekahuna seismograph vault. However, because of the lack of electric power at the Uwekahuna vault, the instrument was operated only for short periods, on an experimental basis. During this brief period the recorder was operated by means of storage batteries and a dc-ac inverter. In March 1951, the installation of an underground power cable was completed from the observatory building to the Uwekahuna vault. It was, however, possible to operate the Sprengnether seismograph only during the time the observatory shop was in operation, about 8 hours a day, 5 days a week. Operation of a Diesel-driven 25-kilowatt generator to supply power for the Sprengnether seismograph proved too expensive, and maintenance of the engine was too difficult.

In September 1951, Roland F. White, observer in charge of the Honolulu Magnetic Observatory of the Coast and Geodetic Survey, installed in the Uwekahuna seismograph vault a Neumann-Labarre vibration meter. The instrument has been loaned to the Hawaiian Volcano Observatory by the Coast and Geodetic Survey, for experimental purposes. Appreciation is expressed to the Coast and Geodetic Survey for the loan of the instrument, and for the assistance of Mr. White in installing it. Appreciation is also expressed to the Coast and Geodetic Survey for the earlier aid of Thomas Pearce in installing and adjusting the Sprengnether seismograph.

Until the end of 1951 the Neumann-Labarre instrument was operated intermittently, at different periods, to determine the optimum conditions for its operation to meet local problems. The boom of the instrument is oriented in an east-west position, because the station lies nearly west of the center of Kilauea caldera and east rift zone of Kilauea, and nearly east of the summit of Mauna Loa.

In April a new tiltmeter was installed in the Uwekahuna vault. This instrument consists of two horizontal pendulums, each weighing about 150 pounds, oriented respectively in north-south and east-west directions. From April until September the pendulums were operated at a period of 29 seconds, but on September 25 the period was reduced to 20 seconds, and kept at that length for the remainder of the year. Until early July the semiportable tiltmeter, installed for temporary service in March 1950, was also operated in the Uwekahuna vault. There was fairly close agreement in the readings of the semiportable tiltmeter and of the new tiltmeter during the period that both were in operation.

Table 1 lists the seismographs and tiltmeters in regular operation in the stations of the Hawaiian Volcano Observatory at the end of

1951. The principal constants of the instruments, and the locations of the stations, also are given. The positions of the stations are shown in figure 31.

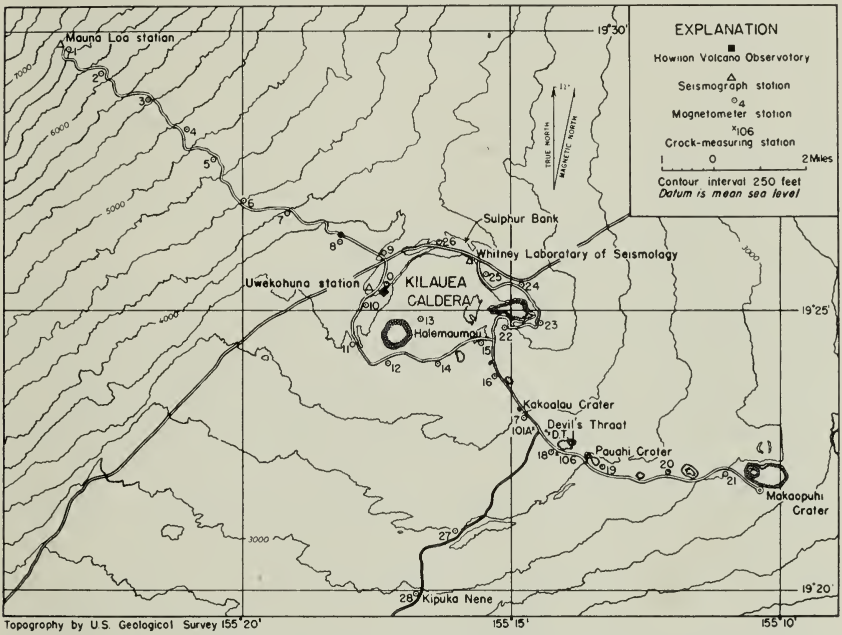

FIGURE 31.—Map showing the location of the Hawaiian Volcano Observatory, seismograph stations, and magnetometer stations, in the vicinity of Kilauea caldera.

TABLE 1.—*Seismographs and tiltmeters operated by the Hawaiian Volcano Observatory during 1951*

Station	Latitude (north)	Longitude (west)	Instrument	Period of pendulum (seconds)	Magnification (approximate)	Sensitivity to tilt (seconds of arc per millimeter)
Whitney Laboratory of Seismology (northeast rim of Kilauea caldera).	19°25′53″	155°15′40″	Bosch-Omori seismograph and tiltmeter.	7.7	115	0.12
Mauna Loa (altitude of 6,600 feet on east slope of Mauna Loa).	19°29′32″	155°23′29″	Hawaiian-type seismograph.	7.1	115	.14
Uwekahuna (1,000 feet west of west rim of Kilauea caldera).	19°25′26″	155°17′36″	Jaggar vertical seismograph.	.4	250	None.
			Sprengnether vertical seismograph.	.5	1,750	None.
			North-south and east-west horizontal pendulum tiltmeters.	20.0	7	.32
Hilo (St. Joseph's School)	19°43′11″	155°05′20″	Modified Bosch-Omori seismograph.	3.0	175	.48
Kona (Konawaena School, Kealakekua).	19°30′47″	155°55′07″	Hawaiian-type seismograph.	7.3	115	.13
Southeast tilt cellar floor of Kilauea caldera southeast of Halemaumau.	19°24′20″	155°16′59″	Normal pendulum tiltmeter.	3	100	1.3
West tilt cellar (floor of Kilauea caldera west of Halemaumau).	19°24′32″	155°17′33″	Normal pendulum tiltmeter.	3	100	1.3

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RECORDS AND INVESTIGATIONS

EARTHQUAKES

A total of 833 earthquakes was recorded on the seismographs at Kilauea caldera in 1951. During the same period, the seismograph at the Mauna Loa station recorded 704 earthquakes. The total number of shocks received at the Kona station is not known, because of incomplete recording during the early part of the year. During the interval from August 23 to December 31 the Kona seismograph recorded 1,276 earthquakes. If the instrument had not been put out of operation temporarily by the heavy earthquake of August 21, it is estimated that the total would have been more than 2,400.

The number of earthquakes recorded per week on the Bosch-Omori seismograph at the Whitney Laboratory, on the northeastern rim of Kilauea caldera, ranged from 0 to 209. The most frequent number was 4, followed by 2 and 9. If the weeks having very high totals caused by swarms of aftershocks following major earthquakes are excluded, the average number per week is 8.9, or slightly more than one earthquake a day. The number of earthquakes per week recorded at the Whitney Laboratory is shown graphically in figure 32.

Swarms of aftershocks followed the Kilauea earthquake of April 22 and the Kona earthquake of August 21. They are discussed in later sections of the report dealing specifically with those earthquakes.

Early on the morning of September 16 an earthquake was felt over most of the southern part of the island. It was reported strong at Kapapala, fairly strong at Naalehu, Pahala, and the Volcano district, and weak in Kona and Hilo. The first waves were registered on the Bosch-Omori seismograph at the Whitney Laboratory at $01^h42^m55^s$ Hawaiian time. The time of origin of the quake was $01^h42^m51^s$ ($11^h42^m51^s$ G. c. t.) The Bosch-Omori seismograph at the Whitney Laboratory, the Jaggar vertical seismograph at the Uwekahuna station, and the Hawaiian-type seismograph at the Mauna Loa station, all were dismantled by the P phase of the earthquake. The S–P intervals recorded on the Hilo and Kona seismographs, and the damage done by the earthquake, place the focus of the quake beneath the southeastern slope of Mauna Loa about 10 miles southwest of Kilauea caldera and about 3 miles northeast of Kapapala, at approximately 19° 19′ N. and 155° 25′ W. The focus of the earthquake probably was along the Kaoiki fault zone. The intensity near the epicenter was about 5 on the modified Mercalli scale. Three miles southwest of the epicenter, at Kapapala Ranch headquarters, objects were thrown from shelves and water slopped out of tanks. Rocks were shaken down in road cuts along the Mauna Loa truck trail in Hawaii National Park, and rock slides started in Halemaumau that continued intermittently

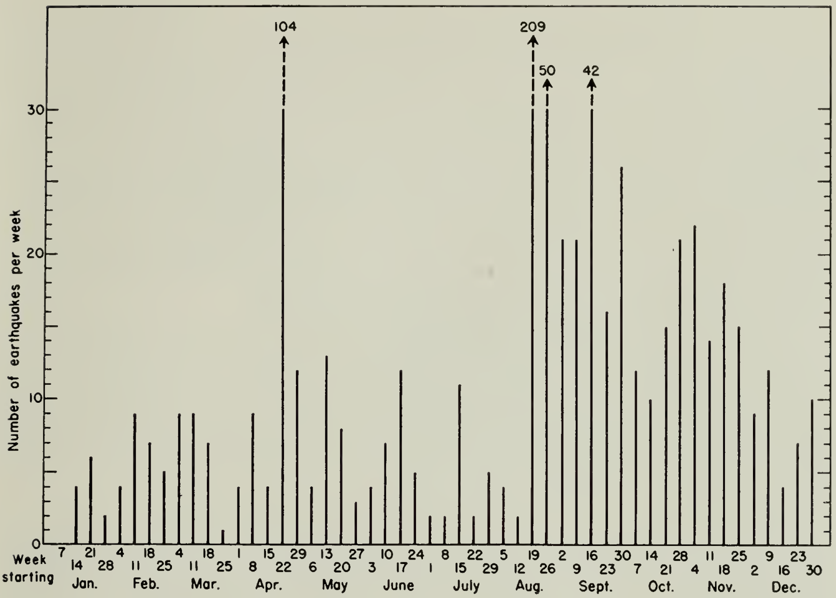

FIGURE 32.—Graph showing the number of earthquakes recorded each week during 1951 at the Whitney Laboratory of Seismology, on the northeastern rim of Kilauea caldera.

for several days. No serious damage was done, however. The major earthquake was followed by 21 small aftershocks, most of which apparently also originated along the Kaoiki fault zone.

Another swarm of small earthquakes that originated along the Kaoiki fault zone between October 1 and 6, bring the total recorded at the Whitney Laboratory during the week starting September 30 to 26.

An earthquake of about intensity 6 in the modified Mercalli scale occurred on the morning of November 8. The time of arrival of the first waves at the Whitney Laboratory was $09^h34^m24^s$, and the time of origin of the quake was approximately $09^h34^m12^s$. All the seismographs operating on the island of Hawaii were dismantled by the quake, the Mauna Loa instrument being dismantled by the preliminary waves. The earthquake was felt over all the island, and was felt strongly over the southwestern part. At Kahuku Ranch headquarters, 9.5 miles north of South Point, dishes were thrown from shelves, and stone walls were extensively damaged. The intensity decreased rapidly away from the epicenter. At South Point, and at Kaalualu, 10 miles southeast from Kahuku Ranch headquarters, there was no damage to stone walls, and in the homestead area 4 miles southeast of ranch headquarters the damage was very small. Westward the decrease was even more rapid. Two and a half miles west of the ranch headquarters stone walls along the highway were undamaged. In-

strumental data and the field investigation place the epicenter of the earthquake on the southwest rift zone of Mauna Loa at an altitude of 4,500 feet, about 5 miles north of Kahuku Ranch headquarters. The Kahuku fault, one of the major fractures in the southwest rift zone, trends nearly north and south just west of the ranch headquarters. The area of damage to stone walls was distinctly elongated parallel to the Kahuku fault, suggesting that the earthquake was caused by movement on that fault. The rapid decrease of damage at increasing distance from the epicenter suggests a shallow origin of the quake, but no surface fault displacement has been found.

At 20^h19^m on December 6 a strong earthquake was felt over the southeastern part of the island of Hawaii. None of the seismographs were dismantled and no damage was reported. The earthquake originated on the east rift zone of Kilauea volcano, about 14 miles east of the caldera and 7 miles southwest of the town of Pahoa, at a depth of 3 or 4 miles.

For more than 20 years the Hawaiian Volcano Observatory has been employing a scale of seismicity, designed to give some roughly qualitative measure of the comparative amounts of energy released by local earthquakes during given periods (Jones, 1932). The scale is an arbitrary one. Seismicity values are derived by assigning a numerical value to each earthquake, depending on its intensity, and totaling these values for the period in question. The intensity assigned to the earthquake depends largely or entirely on the amplitude of the record produced by the earthquake on the seismographs, taking into consideration the magnification of the various instruments. Thus an earthquake producing a record having a double amplitude of 4 to 11 millimeters on the Bosch-Omori seismograph at the Whitney Laboratory is classified as "feeble," and assigned a seismicity value of 1. An earthquake producing a record with a double amplitude of 25 to 60 millimeters on the same instrument is classified as "moderate," and assigned a seismicity value of 3. The grades of earthquake intensity and the seismicity value assigned to each grade, are listed in table 2.

Earthquakes of seismicity value 1 to 4 correspond to about the same numerical grades in the Rossi-Forel and modified Mercalli scales of intensity. Table 2 also indicates the corresponding grades in those scales, and gives a brief description of the noninstrumental effects produced by earthquakes of each grade from 1 to 4. However, because the Hawaiian Volcano Observatory scale is based on instrumental effects, and the other scales on noninstrumental effects, the correspondence is far from exact.

All earthquakes producing a double amplitude of oscillation of more than 60 millimeters on the Boch-Omori seismograph are classified as strong and receive the same seismicity rating.

TABLE 2.—*Comparison of earthquake intensity scales*

Hawaiian Volcano Observatory scale				
Designation	Double amplitude of motion on Bosch-Omori seismograph at the Whitney Laboratory (millimeters)	Seismicity value	Description of noninstrumental effects	Approximate grade in Rossi-Forel and modified Mercalli scales
Tremor	<1/2	1/4	Not felt	
Very feeble	1/2–4	1/2	Not felt, or only rarely felt by few persons in especially favorable positions, usually lying down.	
Feeble	4–11	1	Not felt, or felt only by a few persons in favorable positions.	I
Slight	11–25	2	Felt by many persons at rest. Hanging objects may swing.	II
Moderate	25–60	3	Felt generally, in buildings and out of doors. Hanging objects swing.	III
Strong	>60	4	Felt by nearly everyone. Objects swing. Dishes, doors, and windows rattle. Minor damage may result.	IV

Figure 33 is a graph of weekly seismicity at the Whitney Laboratory, derived in this manner. The curve generally follows that of the number of earthquakes per week, given in figure 32. Table 3 lists the number of earthquakes per week, and the weekly seismicity value, for the Whitney and Mauna Loa stations.

Seismicity at the Whitney Laboratory indicates the degree of earthquake activity, but not the origin, and gives no direct indication of which, if either, volcano is the source of the majority of the activity. Many of the small earthquakes are not sufficiently well recorded to allow positive determination of their origin. However, more of the small earthquakes should be recorded near their origin than at more distant stations. Quakes recorded at both stations should yield a larger record near their origin. Thus the seismicity of stations near the points of origin of the majority of the quakes recorded in any given period should be higher than that of more distant stations. The relative seismicity curve in the upper portion of figure 33 shows graphically the relationship of the Mauna Loa and Whitney stations to the location of origin of the majority of the earthquakes during the year 1951. The value for relative seismicity is derived by assigning a plus value to the seismicity of the Mauna Loa station and a minus value to that of the Whitney Laboratory (Kilauea) station, and adding the two algebraically. A positive residue indicates an excess of Mauna Loa activity over that of Kilauea, and a negative residue indicates conversely that the majority of the earthquake activity originated at Kilauea.

Thus a high total seismicity value combined with a large positive value for the relative seismicity indicates a large amount of earthquake

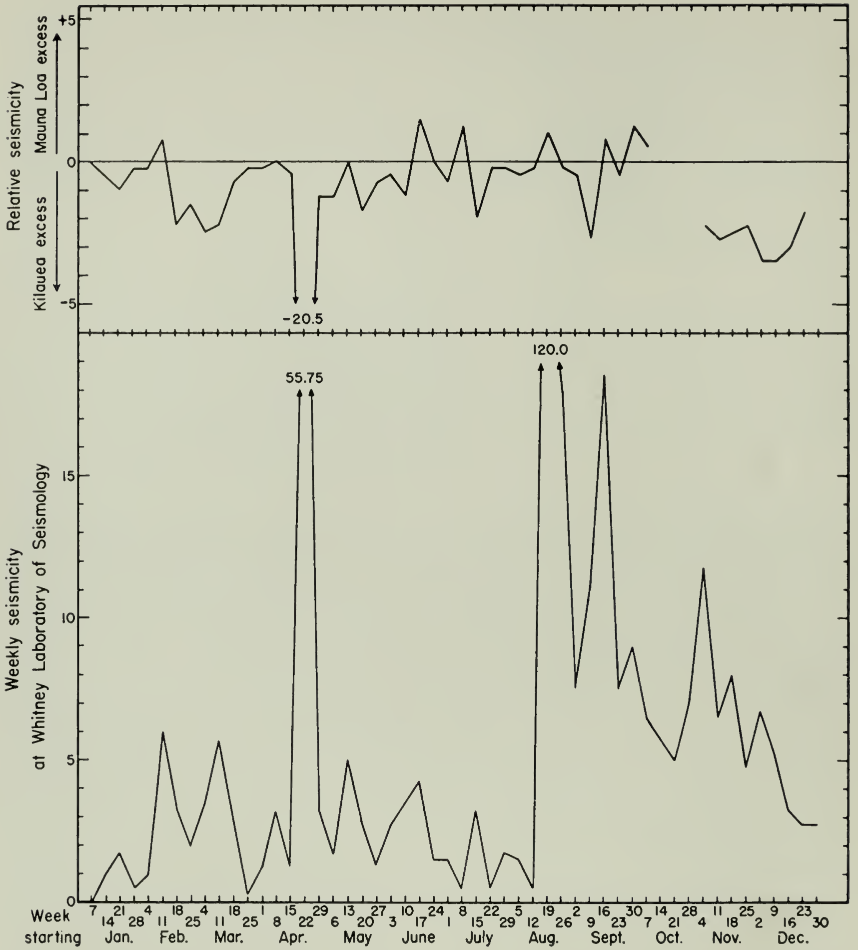

FIGURE 33.—Graph in the lower part showing the seismicity at the Whitney Laboratory of Seismology each week during 1951; and in the upper part the relative seismicity at the Mauna Loa seismograph station and the Whitney (Kilauea) station.

activity originating at Mauna Loa. In figure 33 the high seismicity and strongly negative relative seismicity for the week of April 22 indicates that most of the numerous earthquakes during that week were of Kilauea origin. On the other hand, the high seismicity combined with a low value of relative seismicity during the weeks of August 19 and September 16 indicate that the abundant earthquakes of those weeks were approximately equidistant from the two stations—in Kona and along the Kaoiki fault between Mauna Loa and Kilauea. The relatively very high seismicity during the week of August 19, at the Kona station would indicate clearly, without the other evidence, that the origin of the quakes was near that station.

Table 4 lists the earthquakes of local origin, larger than tremors, recorded during 1951 by seismographs operated on the island of Hawaii by the Hawaiian Volcano Observatory. The time given is the arrival time of the preliminary phase at the Whitney Laboratory of Seismology. It is given to the closest minute in Hawaiian standard time, which is 10 hours slower than Greenwich civil time. If the earthquake was more intense at one of the other stations than it was at the Whitney Laboratory, the intensity rating at the station is given in the column under Remarks.

Table 5 lists the earthquakes of distant origin recorded during the year. The time given is that of the arrival of the first recognizable oscillation at the Whitney Laboratory. The epicenters given in the table are taken from the notices of "Preliminary determinations of epicenters, 1951," published by the U. S. Coast and Geodetic Survey.

TABLE 3.—*Number of earthquakes per week and weekly seismicity*

Week beginning	Whitney station (Kilauea)		Mauna Loa station		Week beginning	Whitney station (Kilauea)		Mauna Loa station	
	Number of earthquakes	Seismicity	Number of earthquakes	Seismicity		Number of earthquakes	Seismicity	Number of earthquakes	Seismicity
January 7	0	0	0	0	July 1	2	1.5	2	0.75
14	4	1.0	2	.5	8	2	.5	7	1.75
21	6	1.75	3	.75	15	11	3.25	5	1.25
28	2	.5	1	.25	22	2	.5	1	.25
February 4	3	.75	3	.75	29	5	1.75	5	1.5
11	9	6.0	5	6.75	August 5	4	1.5	3	1.0
18	7	3.25	4	1.0	12	2	.5	1	.25
25	5	2.0	2	.5	19	209	120	213	121
March 4	9	3.5	2	1.0	26	50	18.75	49	17.75
11	9	5.75	7	3.5	September 2	21	7.5	19	7.0
18	7	2.75	5	2.0	9	21	11.0	21	8.25
25	1	.25	0	0	16	42	18.5	42	19.25
April 1	4	1.25	3	1.0	23	16	7.5	15	7.0
8	9	3.25	6	3.25	30	26	9.0	26	10.25
15	4	1.25	2	.75	October 7	12	6.5	10	7.0
22	104	55.75	65	35.25	14	10	5.75	([1])	([1])
29	12	3.25	8	2.0	21	15	5.0	([1])	([1])
May 6	4	3.0	5	1.75	28	21	7.0	([1])	([1])
13	13	5.0	7	5.0	November 4	22	11.75	16	9.5
20	8	2.75	3	1.0	11	14	6.5	7	3.75
27	3	1.25	2	.5	18	18	8.0	15	5.5
June 3	4	2.75	4	2.25	25	15	4.75	9	2.25
10	7	3.5	6	2.25	December 2	9	6.75	6	3.25
17	12	4.25	14	5.75	9	12	5.25	7	1.75
24	5	1.5	5	1.5	16	4	3.25	1	.25
					23	7	2.75	3	1.0
					30	10	2.75	([1])	([1])

[1] Record incomplete; drum drive stopped.

TABLE 4.—*Local earthquakes recorded at Hawaiian Volcano Observatory during 1951*

Serial no.	Date	Time (Hawaiian standard)	Intensity at Whitney Laboratory	Epicenter	Remarks
		h m			
1	Jan. 3	03 39	Very feeble		
2	6	04 58	Slight	Southwest rift of Mauna Loa at an altitude of about 8,000 feet.	
3	26	06 40	Very feeble		
4	Feb. 14	10 55	Slight	Kaoiki fault near Ainapo	About 7 miles deep. Moderate, Mauna Loa. Felt at Kapapala.
5	16	07 26	do	Northeast rift of Mauna Loa near Puu Ulaula.	About 15 miles deep. Moderate, Mauna Loa. Felt from Hilo to Naalehu.
6	16	18 58	Very feeble		
7	20	20 01	do		
8	20	20 47	do		
9	20	21 47	do		
10	21	21 26	do		
11	23	03 41	do		
12	24	17 39	do		
13	26	01 28	do		Feeble, Kona.
14	26	09 21	do		
15	28	14 13	do		
16	Mar. 5	03 53	do		
17	5	03 56	do		
18	5	09 33	do		
19	5	16 44	do	Northeast rift of Mauna Loa.	
20	8	16 30	do	Nearly under Hilo	About 25 miles deep.
21	14	03 47	do	Hilina fault, southeast of Kilauea caldera.	
22	14	03 48	Feeble	East rift of Kilauea	
23	14	20 50	Slight	East rift of Kilauea, 3 miles east-northeast of Napau Crater.	About 7 miles deep. Felt in Hilo and Volcano areas.
24	15	04 38	Very feeble	West slope of Mauna Loa near Kealakekua.	Feeble, Mauna Loa.
25	15	11 34	do		
26	15	16 43	do	Near Kealakekua	Slight, Kona.
27	20	06 42	Feeble	East slope of Mauna Loa 3 miles east of Kulani cone.	About 6 miles deep. Felt in Puuco district of Hilo.
28	24	06 28	No record	West slope of Mauna Loa	Very feeble, Kona.
29	24	22 33	Very feeble		
30	Apr. 4	10 43	do		
31	13	01 19	do	About 8 miles southwest of Waimea.	Shallow, felt at Waimea.
32	13	14 53	Feeble	East flank of Kilauea	
33	15	13 36	Very feeble		
34	22	04 54	Moderate	East rift of Kilauea 7 miles S. 15° E. of Glenwood.	21 miles deep. Felt at Kapapala and from Volcano district to Hilo.
35	22	14 52	Very strong	East rift of Kilauea near the caldera.	25 to 30 miles deep. Felt all over Hawaii Island, and on Maui and Oahu.
36	22	15 25	Very feeble		
37	22	15 27	do		
38	22	15 41	do		
39	22	15 49	do		
40	22	15 50	do		
41	22	15 51	do		
42	22	16 08	do		
43	22	16 14	do		
44	22	16 49	do		
45	22	17 19	Feeble	East rift of Kilauea 7 miles east of the caldera.	About 8 miles deep.
46	22	17 30	Very feeble		
47	22	18 46	do	Southwest rift of Kilauea near Mauna Iki.	About 5 miles deep.
48	22	20 30	Tremor		Very feeble, Mauna Loa.
49	22	21 11	do		Do.
50	22	23 30	Very feeble		
51	22	23 40	do	Kaoiki fault near Ainapo	
52	23	00 17	do		
53	23	02 46	do		
54	23	03 04	do	Kaoiki fault near Kapapala.	

TABLE 4.—*Local earthquakes recorded at Hawaiian Volcano Observatory during 1951*—Continued

Serial no.	Date	Time (Hawaiian standard)	Intensity at Whitney Laboratory	Epicenter	Remarks
		h m			
55	Apr. 23	03 27	Very feeble		
56	23	04 37	do		
57	23	04 40	Slight	East rift of Kilauea 2 miles south of Makaopuhi Crater.	About 4 miles deep.
58	23	04 41	do	Three miles north of Kilauea caldera.	About 5 miles deep.
59	23	04 44	Feeble	East slope of Mauna Loa near Kulani cone.	About 7 miles deep.
60	23	05 24	Very feeble		
61	23	05 48	Slight	Five miles northwest of Kilauea caldera.	About 6 miles deep.
62	23	06 13	Very feeble		
63	23	06 36	Strong	Southwest rift of Kilauea 2 miles southwest of Maunaiki.	About 5 miles deep.
64	23	21 53	Very feeble	Southwest rift of Kilauea near Puu Koae.	Do.
65	23	22 16	do	East slope of Mauna Loa 2 miles southwest of Kulani cone.	Do.
66	23	22 18	do		
67	24	01 14	do		
68	24	01 29	do		
69	24	11 30	do	Three miles northwest of Kilauea caldera.	About 11 miles deep.
70	25	11 41	do		
71	25	22 38	do		
72	26	00 57	Tremor		Very feeble, Mauna Loa.
73	26	03 58	Strong	East rift of Kilauea near Makaopuhi Crater.	About 12 miles deep. Felt in Volcano district.
74	26	05 51	Feeble	Waimea Plain about 6 miles east of Waimea.	
75	28	07 08	Slight	Four miles east of Kulani cone.	
76	29	16 19	Very feeble	About 3 miles southeast of Kulani cone.	
77	May 6	08 53	Very feeble	Kaoiki fault zone, 3 miles southwest of Pahala.	Felt by 1 person in Volcano district, and some in Pahala and Naalehu.
78	7	12 36	do		
79	8	00 38	Feeble		
80	10	15 24	do	East rift of Kilauea near Puu Huluhulu.	Shallow.
81	13	00 24	Very feeble		
82	14	18 41	do	Southwest rift of Kilauea near Maunaiki.	Do.
83	15	22 10	do		
84	17	12 12	Feeble		
85	18	03 00	Very feeble		
86	20	13 34	do		
87	20	16 16	do		
88	25	03 10	do		
89	30	21 59	do		
90	31	09 13	do		
91	June 3	04 45	Tremor		Very feeble, Mauna Loa.
92	4	14 36	No record at Whitney vault.		Very feeble, Kona.
93	7	22 50	Slight	East rift of Kilauea near Pauahi Crater.	Shallow. Felt in Volcano district and by a few in Hilo.
94	11	08 33	do	East rift of Kilauea 6 miles west of Pahoa.	About 7 miles deep. Felt generally from Hilo to Volcano district.
95	11	19 23	Tremor		Very feeble, Mauna Loa.
96	12	12 12	do		Do.
97	14	11 12	Very feeble		
98	15	13 19	do	Kilauea caldera	
99	17	12 01	do	Nine miles west of Mokuaweoweo.	About 16 miles deep Slight, Mauna Loa.
100	19	05 15	Feeble		
101	22	08 11	Tremor		Very feeble, Mauna Loa.
102	23	01 14	Very feeble		
103	27	07 27	do		
104	27	11 49	Tremor		Do.

TABLE 4.—*Local earthquakes recorded at Hawaiian Volcano Observatory during 1951*—Continued

Serial no.	Date	Time (Hawaiian standard)	Intensity at Whitney Laboratory	Epicenter	Remarks
		h m			
105	July 1	04 07	Very feeble	Southwest rift of Mauna Loa near Sulphur Cone.	
106	5	23 20	Feeble	Kilauea caldera	Shallow.
107	17	09 52	Very feeble		
108	19	19 12	do		
109	Aug. 2	19 24	do		
110	3	01 40	do		
111	6	23 07	do		
112	10	04 31	Feeble	East rift of Kilauea near Napau Crater.	
113	21	00 57	Strong	About 3 miles WNW of Napoopoo, probably on Kealakekua fault.	Much damage in Kona. Intensity 7.
114	21	01 29	do	Near no. 113	Felt strongly in Kona.
115–135	21		Very feeble and feeble.	Kona	
136	21	03 50	Slight	do	Felt from Kona to Volcano district.
137	21	04 00	Moderate	do	Do.
138–148	21		Feeble and very feeble.	do	
149	21	06 03	Slight	do	
150–154	21		Very feeble	do	
155	21	08 03	Moderate	do	
156–161	21		Feeble and very feeble.	do	
162	21	09 38	Slight	do	
163	21	09 57	Strong	do	Do.
164	21	10 12	do	do	
165–167	21		Very feeble		
168	21	18 32	Strong	do	
169	21	21 07	Very feeble	do	
170	21	22 48	Strong	do	Do.
171	22	02 14	Slight	do	
172–174	22		Feeble and very feeble.	do	
175	22	06 38	Moderate	do	Felt from Kona to Kapapala.
176–180	22		Feeble and very feeble.	do	
181	22	16 04	Slight	do	
182	22	16 38	Very feeble	do	
183	22	17 15	Strong	do	Felt from Kona to Volcano district.
184	22	17 28	Slight	do	Felt as far as Naalehu.
185–187	22		Feeble and very feeble.	do	
188–190	23		do	do	
191	24	00 25	Very feeble	Kona, Kealakekua fault	
192	24	23 59	do	Kona	
193	25	10 22	Feeble	Kilauea	
194	25	11 14	Very feeble	Kealakekua fault	Kona feeble.
195	26	03 29	do	do	
196	26	08 04	do	Kona, Pali Kaholo	
197	26	08 11	do	Kealakekua fault	Kona slight.
198	26	19 40	do	Kona 2.3 miles S. 75° E. of Napoopoo.	
199	27	04 31	do	Kealakekua fault	Kona feeble.
200	27	16 01	do	do	
201	27	21 58	do	Kona near Keokea	Kona slight.
202	28	11 44	do	Kealakekua fault	
203	28	14 24	do	do	
204	28	17 48	Feeble	About 3 miles east-southeast of Mountain View.	Felt in Mountain View and Volcano district.
205	28	18 04	Very feeble	Southwest rift of Kilauea near Kilauea Iki.	
206	28	20 28	do	Kealakekua fault	Kona feeble.
207	29	06 02	do	do	Do.
208	29	19 43	do	Kona	Kona slight.
209	29	21 25	do	Kealakekua fault	Kona feeble. Felt in Kona.
210	30	07 23	do	do	Kona moderate. Felt strongly in Kona.
211	30	14 23	do	Kona	
212	31	16 08	do	Kealakekua fault	Kona strong, intensity 5. Felt strongly in Kona.

TABLE 4.—*Local earthquakes recorded at Hawaiian Volcano Observatory during 1951*—Continued

Serial no.	Date	Time (Hawaiian standard)	Intensity at Whitney Laboratory	Epicenter	Remarks
		h m			
213	Aug. 31	18 51	Very feeble	Kona, about 3.5 miles west of Hookena.	Kona feeble.
214	Sept. 1	12 29	Feeble	Kealakekua fault	Kona slight.
215	1	23 21	Very feeble	Kona, about 0.8 mile north of Kealia.	Kona feeble.
216	2	18 35	do		Do.
217	3	00 37	do	Kona	
218	4	00 48	do	do	
219	4	05 10	do	do	Kona moderate.
220	4	14 13	do	Central Kona	Kona strong, intensity 4. Felt strongly in Kona.
221	4	16 16	do	Kilauea caldera	
222	4	22 28	do	Central Kona	Kona strong, intensity 3. Felt as far as Naalehu.
223	6	01 29	do	do	Kona slight.
224	8	14 50	do	Kilauea caldera	
225	8	23.27	Tremor		Kona feeble.
226	9	13 58	do	Central Kona	Kona moderate.
227	10	01 50	Very feeble	Kilauea	
228	10	12 55	do	Kona	
229	11	00 26	Feeble	East rift of Kilauea near Puu Huluhulu.	
230	11	12 44	Very feeble	Kona	
231	12	01 12	do	Central Kona	Kona slight.
232	12	01 27	do		Kona feeble. Felt at Naalehu.
233	12	03 26	Moderate	Southwest rift of Kilauea near Pit Craters.	
234	12	18 55	Very feeble	Kona	
235	12	18 56	do		
236	14	16 49	do		
237	15	16 45	Tremor		Kona, very feeble.
238	15	21 33	Very feeble	Southwest rift of Mauna Loa at altitude of about 9,000 feet.	
239	15	23 48	do		Felt at Kapapala.
240	16	01 43	Strong	Kaoiki fault about 3 miles northeast of Kapapala.	Intensity 5. Felt from Kona to Hilo.
241–250	16		Very feeble	Kaoiki fault	
251	16	21 50	Tremor	Kona	Kona feeble.
252	16	23 19	Very feeble		
253	17	10 17	do	West slope of Mauna Loa near summit.	Kona moderate.
254	17	15 19	Tremor		Mauna Loa, very feeble.
255	17	18 17	Very feeble	Southwest rift of Mauna Loa at an altitude of about 11,000 feet.	Kona feeble.
256	18	08 47	do		
257	19	19 15	do	Central Kona	Kona slight.
258	20	00 11	Tremor		Mauna Loa very feeble.
259	20	00 25	do	Central Kona	Kona slight.
260	20	00 42	Very feeble	do	Do.
261	20	03 21	Tremor		Kona very feeble.
262	21	07 46	Very feeble		
263	21	12 30	Tremor		Kona feeble.
264	23	19 01	Very feeble	Central Kona	Kona strong. Felt strongly in Kona.
265	24	03 01	do	Kaoiki fault 2 miles northeast of Ainapo.	
266	24	03 13	do	Near summit of Hualalai	Kona slight. Felt in Kona
267	24	03 30	Tremor		Kona feeble.
268	24	23 47	Very feeble	East rift of Kilauea about 10 miles east of Kapoo.	Felt in Hilo.
269	25	00 56	do	Northwest rift of Hualalai at an altitude of about 5,000 feet.	Kona feeble. Felt in north Kona.
270	25	01 23	Slight	Near no. 269	Kona moderate. Generally felt in Kona.
271	26	20 20	Very feeble	South slope of Hualalai about 4 miles southeast of Holualoa.	Kona slight. Felt in Kona.
272	26	23 21	do		
273	30	06 21	do	Kilauea	
274	30	11 17	do	do	
275	30	16 06	do	do	

TABLE 4.—*Local earthquakes recorded at Hawaiian Volcano Observatory during 1951*—Continued

Serial no.	Date	Time (Hawaiian standard)	Intensity at Whitney Laboratory	Epicenter	Remarks
		h m			
276	Oct. 1	09 17	Tremor	Central Kona	Kona very feeble.
277	3	22 56	do	do	Do.
278	4	06 01	Very feeble	do	Kona feeble.
279	4	19 03	Tremor	do	Kona very feeble.
280	5	02 09	do	do	Do.
281	5	08 42	Very feeble	Kaoiki fault near Hilea	Felt at Kapapala and Naalehu.
282	6	02 44	do	East edge of Kealakekua Bay.	Kona feeble.
283	6	04 36	Feeble	Kaoiki fault about 4 miles northeast of Kapapala.	Felt at Kapapala and Naalehu.
284	6	08 35	Very feeble	Kaoiki fault about 3 miles northeast of Kapapala.	Mauna Loa slight.
285	6	13 34	Tremor	Central Kona	Kona very feeble.
286	7	01 28	Very feeble	Near Hilea	Felt at Naalehu.
287	7	05 14	Tremor	Central Kona	Kona very feeble.
288	8	07 16	No record		Kona feeble.
289	9	01 40	do		Do.
290	9	04 45	Slight	Central Kona	Felt from Kona to Hilo.
291	9	05 23	Feeble	do	Kona moderate. Felt at Kealakekua.
292	10	02 31	Tremor		Kona very feeble.
293	11	15 05	Very feeble	Kilauea(?)	
294	11	21 30	do	Central Kona	Kona moderate, felt at Kealakekua.
295	12	10 12	do	do	Kona slight.
296	12	16 06	Tremor		Kona very feeble.
297	14	16 37	Very feeble	Kilauea	
298	14	19 52	do		Felt at Naalehu.
299	15	02 43	do	Central Kona	
300	15	19 47	do		
301	17	08 49	Tremor	Central Kona	Kona very feeble.
302	17	21 12	Slight	Northeast rift of Mauna Loa near the 3,000-foot contour.	Mauna Loa moderate. Felt at Volcano and Hilo.
303	19	01 00	Very feeble	Northeast rift of Mauna Loa(?).	Felt at Volcano.
304	20	11 58	do		
305	20	19 10	Tremor		Kona very feeble.
306	20	21 01	Very feeble	Central Kona	Kona feeble.
307	23	10 42	Tremor	do	Kona slight. Felt at Kealakekua.
308	24	13 14	Very feeble	do	Kona feeble.
309	24	13 15	do		Felt at summit of Mauna Loa.
310	25	02 42	do		
311	25	05 22	do		
312	27	21 05	do		
313	28	06 53	Tremor	Central Kona	Kona very feeble.
314	29	02 07	Very feeble	do	
315	29	23 49	do	Kaoiki fault about 3 miles northeast of Hilea.	
316	Nov. 1	20 48	do		
317	3	06 26	do		
318	4	19 24	do	Northeast of Mauna Loa	
319	6	10 44	do	Kilauea	
320	6	11 08	do	do	
321	7	20 11	do	Near summit of Hualalai	
322	7	22 46	do		
323	8	09 34	Strong	Southeast rift of Mauna Loa at an altitude of about 4,500 feet.	Intensity 6 at Kahuku. Felt over the entire southern part of island.
324	8	10 16	Very feeble		
325	8	14 10	Tremor	Central Kona	Kona slight.
326	8	14 22	Very feeble	Kona	Felt at Kealakekua.
327	8	16 33	do	Kilauea	
328	8	23 27	Tremor	Central Kona	Kona very feeble.
329	9	00 55	Very feeble	Hilina fault near Puu Kapukapu.	
330	10	14 16	do	Southwest rift of Mauna Loa at an altitude of about 11,000 feet.	
331	11	03 52	do		
332	11	07 08	Slight	East rift of Kilauea near Pauahi Crater.	Felt in Hilo.

TABLE 4.—*Local earthquakes recorded at Hawaiian Volcano Observatory during 1951*—Continued

Serial no.	Date	Time (Hawaiian standard)	Intensity at Whitney Laboratory	Epicenter	Remarks
		h m			
333	Nov. 12	07 01	Very feeble	Kaoiki fault near Ainapo	
334	13	00 41	do	Kilauea	
335	16	02 57	do	do	
336	16	20 54	do		
337	17	14 50	No record		Kona feeble. Felt in Kealakekua.
338	18	01 31	Tremor		Kona very feeble. Felt at Kealakekua.
339	18	02 47	do	Central Kona	Kona slight. Felt at Kealakekua.
340	18	11 18	Very feeble	Kilauea caldera, near Uwekahuna.	
341	19	18 58	do		
342	20	17 43	Tremor	Central Kona	Kona very feeble.
343	21	06 22	Very feeble		
344	21	10 00	do	Waimea Plain near Kamuela P. O.	
345	21	22 23	do		
346	22	17 37	do	East slope of Mauna Loa about 3 miles east of Kulani cone.	
347	23	08 22	Slight	Kealakekua fault about 5 miles west of Napoopoo.	Kona moderate. Felt from Kona to Kahuku.
348	25	06 17	Tremor		Kona very feeble.
349	25	21 41	do	Central Kona	Do.
350	26	12 35	Very feeble	East rift of Kilauea near Makaopuhi Crater.	
351	26	21 25	Tremor	Central Kona	Kona very feeble.
352	28	09 36	Very feeble		
353	28	11 41	do		
354	Dec. 1	06 09	do	Central Kona	
355	2	12 00	do		
356	3	08 33	do		
357	5	05 20	do	Kilauea caldera	
358	6	20 19	Strong	East rift of Kilauea about 7 miles southwest of Pahoa.	Felt from Kapapala to Hilo and east Puna.
359	9	16 37	Feeble	Near Kilauea caldera	
360	11	02 12	Very feeble		
361	11	13 58	do		
362	12	16 51	do		
363	13	03 06	Tremor	Central Kona	Kona feeble.
364	13	21 54	Very feeble	Kilauea caldera	
365	14	19 22	Tremor	Central Kona	Kona very feeble.
366	15	01 36	Very feeble		
367	15	23 16	do		
368	17	15 48	do		
369	19	05 30	do		
370	23	09 31	do	Kilauea caldera	
371	25	09 50	do		
372	26	23 06	do		
373	28	16 17	Tremor	Central Kona	Do.
374	29	08 45	No record	do	Kona feeble.
375	29	17 32	Very feeble	Kaoiki fault near Pahala	Felt at Naalehu and Kapapala.
376	30	02 00	No record	Central Kona	Kona feeble.
377	31	15 49	Tremor	do	Do.

TABLE 5.—*Distant earthquakes recorded at Whitney Laboratory, Hawaiian Volcano Observatory, during 1951*

Date	Time (Hawaiian standard)	Strength at Whitney Laboratory	Epicenter (From preliminary determinations of epicenters by U. S. Coast and Geodetic Survey)
	h m		
Jan. 13	12 20	Slight	About 150 miles east of Alaska Peninsula.
17	11 17	do	Southeastern New Guinea.
Feb. 19	12 38	Moderate	About 500 miles west of Easter Island.
Mar. 10	12 06	Slight	Fiji Islands region.
Apr. 30	05 35	do	Celebes region.
May 19	04 59	do	
19	06 45	do	South-central Spain.
June 16	23 54	do	About 300 miles off the coast of Oregon.
Aug. 31	23 16	do	Easter Island region.
Sept. 27	09 40	Moderate	Vancouver Island.
Oct. 21	11 46	Slight	Formosa.
21	17 41	do	Do.
Nov. 6	06 53	do	Kurile Islands.
8	04 02	Moderate	Aleutian Islands.
Dec. 7	18 35	Slight	Indian Ocean about 900 miles southeast of Madagascar.
25	15 03	do	Off coast of southern California.
27	23 34	do	Guerrero, Mexico.
30	12 50	Moderate	Pacific Ocean, west of Easter Island.

TILTING OF THE GROUND

Tilting of the ground surface, and its relationship to Hawaiian volcanism, were discussed at some length in the report of the Hawaiian Volcano Observatory for 1950 (Finch and Macdonald, 1953). The reader is referred to that report for the discussion, which will not be repeated here.

Figure 34 is a graph showing the north-south and east-west components of the tilting of the ground surface measured at the Whitney Laboratory of Seismology by means of the Bosch-Omori seismograph. The approximate average annual tilt curves in the two components, determined for years in which there was no surficial volcanic activity, also are shown in the figure. The vertical position of this average curve on the graph may not have any significance. However, any marked variation in the general form of the curve of actual measured tilt from that of the average curve is probably the result of variations in volcanic conditions, presumably largely subsurface magmatic pressure. Thus a rise of the north-south tilt curve at a rate much greater than the average curve apparently represents an increase of pressure beneath Kilauea volcano, with an accompanying rise of the ground surface near Halemaumau and a north-northeastward tilting of the surface at the Whitney Laboratory. Conversely, a decline of the north-south tilt curve at a rate faster than the average probably reflects a decrease of pressure beneath Kilauea.

The significance of the east-west tilt curve is somewhat more difficult to ascertain. As pointed out in the Hawaiian Volcano Observatory report for 1950 (Finch and Macdonald, 1953), there apparently is some correlation between east-west tilting at the Whitney Laboratory and volcanic conditions at Mauna Loa. The distance of the station

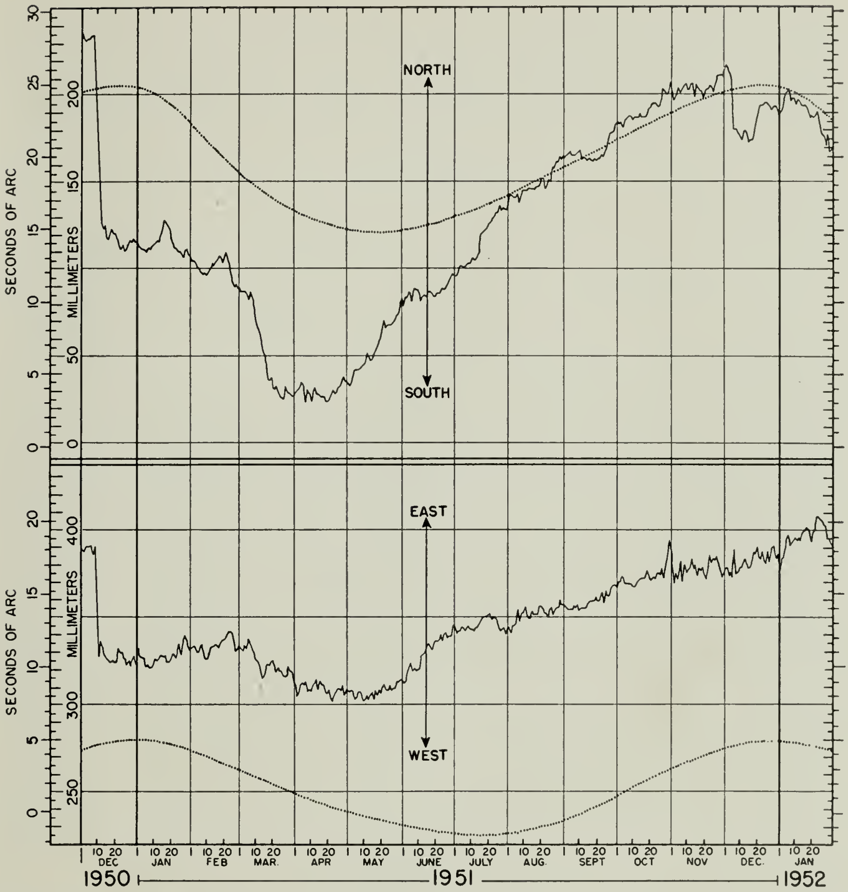

FIGURE 34.—Graph showing ground tilting at the Whitney Laboratory of Seismology, on the northeastern rim of Kilauea caldera, in 1951. The solid line shows the tilt as measured during the year. The dotted line is the approximate normal annual curve for years in which there is no volcanic disturbance.

from the volcano is so great, however, that the expectable tilting from that cause is small. Ascertaining the tilt curve is further complicated because the Whitney station lies slightly east, as well as north, of the center of Kilauea caldera, and tumescence of Kilauea volcano would be expected to produce some eastward component of tilt at the Whitney station. The apparent degree of correlation between volcanic episodes at Mauna Loa and east-west tilting at the Whitney Laboratory may actually be partly the result of a sympathy of action between Mauna Loa and Kilauea, resulting in a simultaneous tumescence and detumescence of the two volcanoes. Thus eastward tilting at the Whitney Laboratory preceding a Mauna Loa eruption might be caused by increase of pressure beneath Kilauea accompanying that beneath Mauna Loa. A longer period of record and further analysis of the tilt

curves are necessary to determine fully the significance of eastward tilting at the Whitney Laboratory.

Table 6 lists the direction and amount of the tilting of the ground surface at the Whitney and Uwekahuna stations for each week of 1951.

TABLE 6.—*Ground tilting at seismograph vaults on the rim of Kilauea caldera, during 1951*

Week beginning	Whitney vault (northeast rim)		Uwekahuna vault [1] (west rim)	
	Direction	Amount (seconds of arc)	Direction	Amount (seconds of arc)
Dec. 31	S. 45° W.	0.9	S. 56° W.	0.4
Jan. 7	N. 38° E.	.8	S. 26° W.	.7
14	N.	.7	N. 70° W.	1.5
21	S. 35° E.	2.0	N. 15° W.	2.4
28	S. 37° W.	.6	N. 27° E.	.2
Feb. 4	S. 45° W.	1.2	S. 70° E.	1.2
11	N. 38° E.	1.5	S. 58° W.	1.5
18	S. 35° E.	1.5	N. 58° W.	1.8
25	S. 42° W.	1.6	N. 78° E.	2.4
Mar. 4	S. 26° W.	2.1	E.	1.5
11	S. 5° W.	4.1	S. 15° E.	.7
18	S. 16° W.	1.2	S. 79° E.	.5
25	W.	.6	N. 63° E.	.4
Apr. 1	N. 45° W.	.5	S. 74° W.	.9
8	S. 63° E.	.8	N. 45° W.	.3
15	S. 85° W.	1.3	S. 72° W.	.2
22	N. 22° E.	1.4	S. 62° W.	1.4
29	N. 27° W.	.4	N. 74° W.	.6
May 6	N. 7° W.	1.0	N. 81° W.	1.1
13	N. 17° E.	1.2		
20	N. 18° E.	1.1	S. 9° E.	2.8
27	N. 15° E.	1.9	S. 19° E.	.4
June 3	N. 60° E.	1.0	S. 17° E.	1.4
10	S. 86° E.	1.6	N. 3° W.	2.1
17	N. 56° E.	.4	N. 17° W.	1.4
24	N. 52° E.	1.4	N. 53° W.	.6
July 1	N. 9° W.	.7	N. 45° E.	.2
8	N. 16° E.	.8	S. 9° E.	1.1
15	N. 6° E.	2.2	S.	3.9
22	N. 26° W.	1.1	N. 24° E.	2.7
29	N. 18° E.	.8	S. 45° E.	1.9
Aug. 5	N. 36° E.	.6	N. 32° W.	4.2
12	N. 67° E.	.9	S. 4° W.	2.4
19	N. 26° W.	1.3	S. 9° W.	5.0
26	N. 40° E.	.9	S. 5° W.	1.8
Sept. 2	N. 27° E.	.3	N. 7° E.	2.6
9	S. 34° E.	.6	S. 68° W.	.8
16	N. 67° E.	.6	S.	5.0
23	N. 10° E.	1.7	S. 16° W.	2.3
30	N. 10° E.	.7	S. 20° E.	2.0
Oct. 7	N. 45° E.	.3	S. 45° E.	.4
14	N.	.7	N. 18° W.	1.0
21	N. 6° E.	1.2	N. 22° W.	5.1
28	S. 31° E.	.7	N. 10° W.	5.2
Nov. 4	N. 22° E.	.6	S.	4.8
11	S. 45° W.	.2	S. 18° E.	3.0
18	N. 74° E.	.9	N. 8° W.	2.0
25	N. 25° W.	1.4	S. 13° E.	3.3
Dec. 2	S. 5° W.	4.2	N. 10° W.	2.0
9	S. 23° E.	.9	N. 10° W.	2.0
16	N. 23° E.	2.8	S. 5° E.	4.2
23	S. 72° E.	.4	S. 34° E.	1.2
30	N.	.5	N. 7° W.	5.1

[1] Record before May 13 is based on a small semiportable tiltmeter. During early May a pair of heavy horizontal pendulums was installed, and the record after May 20 is based on this new instrument. The record for the week starting May 13 is considered unreliable because of improper operation of the east-west pendulum.

Tilt records at the Uwekahuna station are too short for their significance yet to be fully known. By analogy with the records from the Whitney station, it is to be expected that an increase of pressure beneath Kilauea caldera will cause a westward tilting of the ground at the Uwekahuna station, near the western rim of the caldera. Likewise, a decrease of pressure should probably cause an eastward tilting at the Uwekahuna station. A marked eastward tilting at Uwekahuna did accompany the Kilauean subsidence of December 1950, which simultaneously produced a south-southwestward tilting at the Whitney Laboratory. Thus it is probable that major changes in volcanic pressure beneath Kilauea will be clearly reflected by tilt changes at the Uwekahuna station. Since, however, the station lies almost directly between Kilauea and Mauna Loa, a simultaneous increase or decrease of pressure under the two volcanoes may cause little tilting at the Uwekahuna station. This is particularly true if a large change under distant Mauna Loa is accompanied by a smaller sympathetic change under nearby Kilauea. Results to date also suggest that ground tilting at the Uwekahuna station may be much more affected by short-period changes in air temperature, and other weather changes, than is the tilting at the Whitney Laboratory.

The apparent changes in volcanic pressure indicated by the comparison of the tilting actually measured during the year with the average curve, in figure 34, are discussed in a later section of the report, under the heading "Volcanic conditions during 1951."

CRACK MEASUREMENTS

Measurements of crack widths were made at 13 stations, at monthly intervals throughout 1951. The measurements, including those for December 1950 for comparison, are given in table 7. The locations of the crack-measuring stations are shown in figures 31 and 35.

Crack-measuring stations 5 to 9 lie along a series of cracks near and parallel to the southeastern rim of Halemaumau, at the observation area provided for tourists. Station 5, near the northern end of the series of cracks, showed consistent opening throughout 1951, the total opening from December 31, 1950, to December 31, 1951, being 7.2 centimeters (2.8 inches). Station 6 showed a net opening of 1.4 centimeters during the year, and station 7 a net opening of 0.3 centimeter. Station 8 showed no net change during the year, and station 9, near

the southern end of the crack, showed a net closing of 0.3 centimeter. Thus the block bounded by the series of cracks apparently is moving toward the crater at its northern edge, but slightly away from the crater at its southern end.

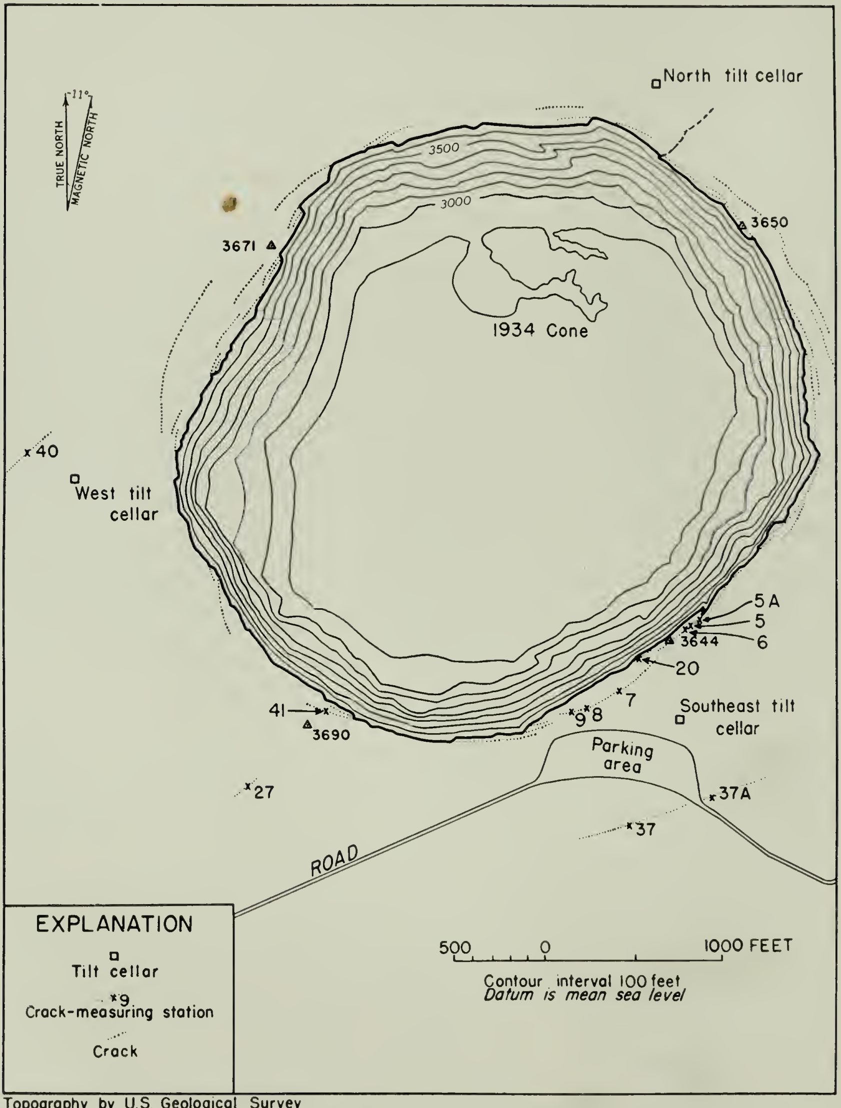

FIGURE 35.—Map of Halemaumau and vicinity, showing the location of tilt-measuring stations and crack-measuring stations.

The cracks at stations 37 and 37A, on the caldera floor east of Halemaumau, showed a small net opening during the year. However, the cracks at stations 40 and 41, west and south of Halemaumau, showed essentially no change. Along the east rift zone of Kilauea volcano, the

crack at station 101A opened 2.5 centimeters during the year, but those at stations 106 and DT-1 showed no significant change.

TABLE 7.—*Width of cracks at Kilauea during 1951 (in centimeters)*

Date	Measuring station number													
	Halemaumau rim cracks						Cracks on floor of caldera					Cracks on east rift		
	5	6	7	8	9	27	37 N-S	37 E-W	37A	40	41	101A	106	DT-1
Dec. 31	109.4	59.3	34.7	58.0	77.9	64.2	49.0	44.5	64.3	33.1	33.4	127.6	101.5	36.0
Jan. 30	109.6	59.4	34.7	58.0	77.9	64.2	49.0	44.5	64.3	33.1	33.4	128.6	101.5	36.0
Mar. 1	109.9	59.5	34.7	58.0	77.8	64.2	49.0	44.6	64.3	33.1	33.4	129.0	101.5	36.0
31	110.5	59.7	34.8	58.1	77.7	64.2	49.1	44.6	64.3	33.1	33.4	128.6	101.5	36.0
Apr. 23	111.1	59.7	34.8	58.0	77.7	64.4	49.1	44.7	64.3	33.1	33.4	129.0	101.6	36.0
May 1	111.4	59.8	34.7	58.0	77.7	64.5	49.1	44.7	64.2	33.1	33.4	128.6	101.5	36.0
31	111.9	59.9	34.9	58.0	77.7	64.5	49.2	44.7	64.3	33.0	33.4	129.0	101.6	36.0
July 2	112.2	60.1	35.0	58.1	77.6	64.5	49.3	44.9	64.4	33.1	33.4	129.0	101.6	36.0
31	112.5	60.2	35.0	58.1	77.7	64.6	49.3	44.8	64.4	33.1	33.4	129.0	101.7	36.0
Aug. 21	113.3	59.9	35.0	58.0	77.7	64.7	49.3	44.8	64.4	33.1	33.4			
31	113.7	59.9	35.2	57.9	77.7	64.8	49.3	44.9	64.4	33.0	33.4	128.8	101.5	36.0
Sept. 30	114.4	60.2	35.1	58.0	77.6	64.9	49.4	45.0	64.4	33.1	33.4	129.2	101.4	36.0
Nov. 1	115.1	60.2	35.1	58.0	77.6	64.9	49.5	45.0	64.5	33.1	33.4	128.9	101.4	36.0
30	115.9	60.5	35.0	57.9	77.7	64.9	49.5	45.1	64.5	33.1	33.5	129.2	101.5	36.0
Dec. 31	116.6	60.7	35.0	58.0	77.6	64.9	49.5	45.1	64.5	33.1	33.5	130.1	101.6	36.0

GEOMAGNETIC OBSERVATIONS

For the past several years the staff of the Hawaiian Volcano Observatory has wanted to start geomagnetic measurements at Kilauea and Mauna Loa volcanoes. Results obtained by workers on volcanoes in other areas, especially Japan (Kato, 1933–35; Takahasi and Hirano, 1941; Rikitake, 1951) have suggested that magnetic measurements in Hawaii might give information on magmatic conditions and movements beneath the surface, and might supplement other methods in predicting eruptions. Preliminary studies by Omer (1945) suggested some correlation between volcanic conditions on the island of Hawaii and small variations in the magnetic field at Honolulu. nearly 200 miles away.

The opportunity to begin magnetic studies came early in 1950, when two Wolfson vertical magnetometers were made available to the Hawaiian Volcano Observatory by the U. S. Geological Survey. H. R. Joesting and J. H. Swartz, accompanied by R. E. Wilcox, spent the first three weeks of February at the Observatory setting up procedures, calibrating instruments, and instructing the Observatory personnel in their use.

Theoretically, the rise of hot magma beneath the volcano should result in a decrease of the strength of the magnetic attraction, and consequently a decrease in the strength of the vertical component of the earth's magnetic field above the heated area. This effect was observed by Rikitake (1951, p. 180) during the 1950 eruption of Ooshima Volcano in Japan.

Permanent observation stations were established during February and March 1950 on Kilauea and the lower slopes of Mauna Loa. The location of the stations is shown in figure 31. The number of stations is not as great as might be desired, but is limited by the time available for the work.

Each station was set at a point where closely spaced setups of the magnetometer showed the magnetic field to be reasonably regular over an area of about 100 square feet. At each station three concrete hubs were set and small pits drilled in them to receive the ends of the magnetometer tripod legs (fig. 36). The tripod legs are kept at a fixed length when the stations are occupied, and each leg is placed on the same hub in successive readings at each station. The leveling screws also are turned out as nearly as possible to the same distance for each setup. Thus the position of the instrument, horizontally and

FIGURE 36.—Magnetometer set up for observations on one of the permanent stations. Concrete cups for tripod legs facilitates achieving the same position of the instrument at each reoccupation.

vertically, is as nearly as possible the same for successive readings at a given station.

Observations of the intensity of the vertical component of the earth's magnetic field were made at each of the stations about once a month throughout the remainder of 1950–51. All the readings of each set were made on the same day, or on two successive days.

The procedure is as follows: One instrument is set on station 0, near the Observatory at the western edge of Kilauea caldera (fig. 31). After the reading at station 0 is obtained the instrument is taken to each of the other stations and readings obtained. Readings are made with the north end of the balance pointed first east and then west, and the average of the two sets of readings is used, thus compensating for any small errors in orientation and leveling of the instrument. Until May 1951, immediately after the first instrument was removed from station 0, the second was set up at that station, and read at frequent intervals throughout the time the first instrument was in use at the other stations. From the readings at station 0 a curve of diurnal variation was constructed which was used in correcting the readings at the other stations. At the end of the traverse the first instrument was again set on station 0, and after correcting for diurnal variation any closing error is distributed linearly throughout the time of operation. The diurnal variation was very small in comparison with the changes in values between successive readings at individual stations. Consequently, because of shortage of personnel at the Observatory, since May, 1951, only one instrument has been used and the correction for diurnal variation has been neglected. The instrument is recalibrated for sensitivity in the laboratory every two or three months. The corrected scale readings are converted into gammas, and the value at each station is recorded in terms of difference in gammas from the value at station 0.

The program is not ideal, but it represents the best results that can be obtained for the available time and the small size of the Observatory staff. It is hoped that the program can be expanded and improved in the future, if results justify it. The values obtained thus far are shown in table 8.

Joesting and Swartz again visited the Observatory in June, 1950, during the eruption of Mauna Loa, for the purpose of checking on the progress of the investigation and the operation of the instruments. Of the measurements listed in the table, those for June 12 were made by them. The others were made by members of the Observatory staff, assisted during March and April by J. B. Orr of the National Park Service. On March 8–9, 1951, F. C. Farnham of the Geological Survey made measurements with an absolute magnetometer at station 0 near the Observatory, and at a newly established station near the seismograph station at St. Joseph's School in Hilo.

TABLE 8.—*Difference in vertical intensity of geomagnetism (in gammas) at stations on Mauna Loa and Kilauea, compared to that at station 0*

All readings for station 0 are actual values. Other values for the month are differences from this reading

Magnetometer station no.	1950											
	Feb. 17	Mar. 20	Apr. 3–4	May 9–10	June 9	June 12	July 15–16	Aug. 12–13	Sept. 21–22	Oct. 21	Nov. 28–29	Dec. 28
0	+234	+156	+163	+149	+160	+203	−130	−313	−307	−381	−240	+186
1	-------	−683	−744	−828	−794	−795	−864	−823	−806	−847	−1003	-------
2	-------	−37	−54	−18	-------	−36	−60	−84	−1	−35	−228	-------
3	-------	−271	−303	−301	−329	−304	−348	-------	−300	−364	−508	-------
4	-------	−291	−345	−326	-------	−327	−400	−342	−326	−371	−551	-------
5	-------	+77	+57	+62	+83	+112	+96	+77	+131	+26	−85	-------
6	-------	−117	−141	−176	-------	−117	−148	-------	−136	−121	−336	-------
7	-------	−76	−107	−120	−115	−82	−110	-------	−79	−75	−339	-------
8	-------	−615	−659	−765	-------	−710	−762	−728	−697	−692	−976	−756
9	-------	−714	−758	−899	−865	−835	−901	−834	−793	−834	−1098	−869
10	−681	-------	−669	−760	-------	-------	−785	−705	−676	−676	−1019	−778
11	−171	-------	−204	−212	-------	-------	−244	−166	−143	−155	−497	−177
12	−677	-------	−676	−745	-------	-------	−760	−696	−658	−676	−1053	−700
13	-------	-------	−536	−604	-------	-------	−588	−559	−541	−541	−919	−506
14	−35	-------	−69	−45	-------	-------	−31	−19	−21	−26	−443	−30
15	+416	-------	+433	+486	-------	-------	+452	+456	+437	+437	+73	+466
16	-------	-------	+177	+198	-------	-------	+178	+217	+217	+217	+209	+168
17	-------	-------	−663	−740	-------	-------	−758	−684	−685	−732	−672	−666
18	-------	-------	−418	−473	-------	-------	−466	−451	−411	−454	−791	−441
19	-------	-------	+287	+353	-------	-------	+326	-------	+313	+352	+16	+332
20	-------	-------	−273	−304	-------	-------	−283	−258	−258	−310	−581	−311
21	-------	-------	+257	+288	-------	-------	+311	-------	+319	+294	+67	+274
22	+786	-------	+784	+899	-------	-------	+894	-------	+845	-------	+697	+823
23	-------	-------	+1167	+1358	-------	-------	+1334	+1255	+1219	-------	+1168	-------
24	-------	-------	−46	−45	-------	-------	−47	−50	−7	-------	−186	-------
25	-------	-------	-------	+2547	-------	-------	-------	+2550	+2591	-------	+2555	-------
26	-------	-------	+243	+288	-------	-------	+291	+289	+276	-------	+189	-------
27	-------	-------	-------	−872	-------	-------	−910	−850	−827	−896	−895	-------
28	-------	-------	-------	−927	-------	-------	−921	−925	−897	−957	−958	-------

TABLE 8.—*Difference in vertical intensity of geomagnetism (in gammas) at stations on Mauna Loa and Kilauea, compared to that at station 0*—Continued

[All readings for station 0 are actual values. Other values for the month are differences from this reading]

Magnetometer station no.	1951											
	Jan. 20–21	Feb. 24	Mar. 20	Apr. 14	May 24–25	June 26–27	July 20–21	Aug. 22–24	Sept. 24–25	Nov. 2–3	Dec. 7–8	Dec. 26
0	+212	+471	+405	+400	+249	+836	+418	+471	+370	+356	+365	+294
1	−821	−792	−858	−602	−853	−800	−862	−854	−891	−953	−929	−868
2	−87	−13	−46	+159	−9	−66	−84	−58	−90	−105	−90	−66
3	−348	−247	−524	−83	−293	−312	−339	−374	−337	−347	−341	−356
4	−368	-------	−486	−158	−297	−347	−378	−278	−346	−432	−337	−384
5	+73	+233	−81	+295	+111	+102	+35	+210	+123	+47	+14	+80
6	−139	-------	−308	+58	−138	−110	−185	−119	−166	−185	−137	−147
7	-------	−66	-------	+22	−129	−79	−172	−18	−71	−110	−14	−176
8	−724	−625	−1060	−836	−715	−708	−774	−766	−763	−816	−711	−664
9	−912	−766	−1179	−924	−880	−831	−893	−898	−853	−972	−863	−711
10	-------	−629	−1052	−761	−849	−704	−717	−775	−654	−787	−735	−647
11	-------	-------	−290	−224	−347	−132	−114	−194	−204	−143	−209	−56
12	-------	-------	−339	−748	−871	−616	−651	−964	−687	−674	−877	−747
13	-------	−431	-------	−484	−738	−616	−427	−445	−592	−473	−588	−510
14	-------	−62	−216	+40	−253	−62	+5	−40	+5	+61	−38	−28
15	-------	+621	+788	+524	+182	+453	+511	+462	+517	+573	+526	+536
16	+199	+306	+526	-------	+267	+216	+216	+198	+308	+294	+204	+327
17	-------	−609	−367	−712	−1031	−690	−783	−704	−640	−777	−810	−706
18	−460	−345	−178	−374	−791	−444	−440	−457	−337	−512	−450	−427
19	+331	+414	+598	+414	+9	+352	+299	+290	+497	+360	+408	+397
20	−280	−180	−18	−228	−507	−250	−286	−304	−157	−237	−265	−261
21	+279	+398	+552	+352	+62	+330	+264	+303	+559	+351	[1]+1550	+351
22	+1108	-------	+889	+863	+493	+858	+871	+889	+1010	+995	+972	+953
23	+1284	-------	+1278	-------	+1083	+1170	+1210	+1201	+1384	+1469	+1427	+1375
24	−8	-------	−123	-------	−280	−110	−119	−79	−61	−38	−171	−113
25	+2602	-------	+3843	-------	+2718	+2652	+1504	+2503	+2768	+2839	+2786	+2720
26	+342	-------	-------	+291	+320	+229	+255	+193	+303	+284	+370	+251
27	−924	−937	−825	-------	−821	−884	−928	−805	−740	−976	[1]+285	−993
28	−976	−994	−920	-------	−874	−919	−928	−885	−778	−882	[1]+166	−965

Readings confirmed by repetition.

Early in July 1950, soon after the end of the Mauna Loa eruption, three stations were established. These extended southeastward for 1.5 miles from a point on the recently active rift at an altitude of about 8,530 feet. A fourth station was established 8 miles farther south-southeast, near the upper access road of the Kahuku Ranch. The latter station lies about 4 miles east of the southwest rift zone of Mauna Loa, but 7.4 miles from the nearest point of eruption during 1950. The locations are shown in figure 41. Readings at these stations were repeated in November 1950 and February 1951. The values obtained are given in table 9, expressed as the difference (in gammas) between the value at the station and that at the base station near the Observatory. The gradually increasing negativity at stations *A*, *B*, *C* may possibly have resulted from a slow warming up of the terrane in the vicinity of the rift by the outward conduction of heat from hot intrusive bodies along the rift. Erratic behavior was observed at station *D*, located on newly erupted lava only 75 feet from the eruptive fissure. This behavior may have resulted from a rapid cooling of the new lava directly beneath the station, followed by some rewarming of the lava heat conducted upward from intrusive masses at depth along the fissure.

TABLE 9.—*Vertical intensity of geomagnetism (in gammas) at stations near the southwest rift of Mauna Loa, in comparison with that at station 0, near the Hawaiian Volcano Observatory*

Date	Station			
	Kahuku *A* (4 miles east of rift)	Kahuhu *B* (1.4 miles east of rift)	Kahuku *C* (0.4 mile east of rift)	Kahuku *D* (at rift)
July 10–12, 1950	+199	+365	+1080	−636
November 2–3, 1950	−211	+182	+1093	+136
February 9–10, 1951	−246	+115	+423	−242

It is too soon to attempt an interpretation of the results of the geomagnetic measurements at the permanent stations on Kilauea volcano and the adjacent southeastern slope of Mauna Loa. Thus far it can be stated definitely only that there are marked changes in the vertical magnetic field both at individual stations, and at groups of related stations as compared with other groups of stations.

Curves *A*, *B*, and *C*, in figure 37, indicate the changes in the relative magnetism between a group of stations (1 to 5) on the slope of Mauna Loa, and groups on Kilauea volcano. Group 10 to 14 lies within Kilauea caldera, group 16 to 21 lies along the east rift zone of Kilauea, and stations 27 and 28 lie on the southern slope of Kilauea about 5 miles south of the caldera. Curve *D* indicates a similar variation between stations in Kilauea caldera and those on the southern slope of Kilauea. The use of groups of related stations minimizes the oc-

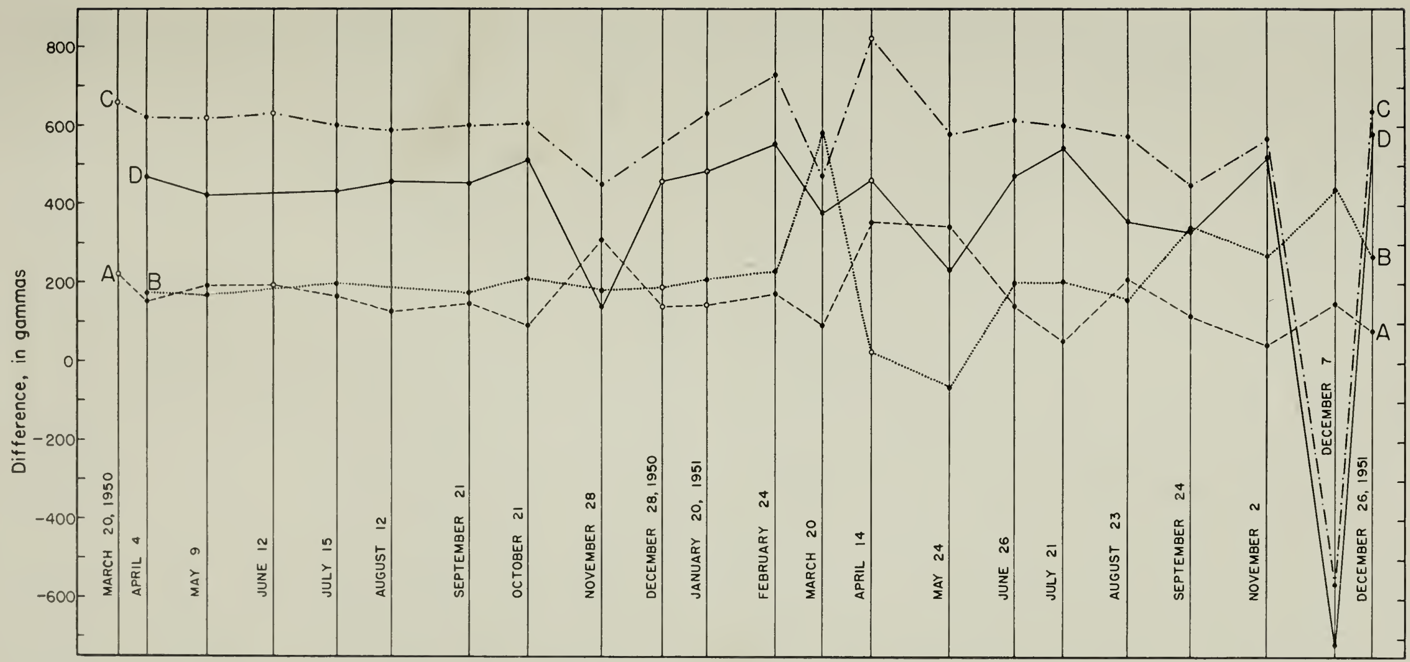

FIGURE 37.—Graph showing differences in vertical intensity of geomagnetism, in gammas, at successive readings, between groups of stations on Mauna Loa and Kilauea volcanoes. Curve *A* shows the change in differences of the average of the values at stations 1 to 5, on Mauna Loa, from the average of the values of stations 10 to 14, in the caldera of Kilauea. Curve *B* shows the change in differences of the average of the values of stations 1 to 5 from that of stations 16 to 21, on the east rift zone of Kilauea. Curve *C* shows the change in differences of the average of the values of stations 1 to 5 from that of stations 27 and 28, on the south flank of Kilauea. Curve *D* shows the change in differences of the average of the values of stations 10 to 14, in Kilauea caldera, from that of stations 27 and 28, on the south flank of the volcano. The solid circles are points for which the data are complete for both sets of stations. The open circles are points for which the data are interpolated for one set of stations from the values for the adjacent months.

casional large, apparently aberrant, changes that occur at single stations. In these curves no distinct reflection of the eruption of Mauna Loa in June 1950, can be detected. Neither is there any distinct reflection of the withdrawal of magma which probably accompanied the subsidence at Kilauea caldera in December 1950. The sharp jog in the curves caused by the readings in late November 1950, may possibly be related to the December subsidence. The change in strength of the vertical magnetic field at Kilauea caldera, as compared with the Mauna Loa stations, is in the right direction (increase) to have been caused by withdrawal of heated material in the area beneath the caldera. However, the duration of the change was much less than would be expected if it was caused by magmatic withdrawal. The direction of the change as related to the stations remote from the caldera on the southern slope of Mauna Loa is the reverse of that which would be expected. The changes in March 1951, and the great increase in magnetic attraction at stations 21, 27, and 28 during early December 1951, can not be correlated with any known volcanic events.

Events such as the 1950 eruption of Mauna Loa, and the subsidence of Kilauea in December 1950, involve the movement of great masses of hot material at depth. At what depths these movements occur is not definitely known, but certain earthquake evidence suggests that it may occur at depths of 20 miles or more. The total areal spread of the permanent magnetometer stations is less than that amount, and it may be, therefore, that the resultant differences in magnetism at the separate group of stations might be too small to be recognized. Too much emphasis should not, therefore, be put on the significance of the curves in figure 37.

TEMPERATURE MEASUREMENTS

Measurements of the temperature of steam escaping at Sulphur Bank (fig. 31), 0.2 mile northwest of the Whitney Laboratory of Seismology, have been continued at monthly intervals throughout 1951. Measurements were made at natural vents, and at the drilled well (Finch and Macdonald, 1951, p. 116). The temperature at the steam well showed little variation. On December 30, 1950, and January 30, 1951, it was 95.5 C. On March 1, the temperature had increased slightly to 96 C., and remained at that reading until October 1. On November 1, December 14, and December 31 it was 95.5 C. (Boiling point of water at this altitude is about 95.7 C.) The greater abundance of rain during the winter months may, in the absence of other factors, cause a slightly lower temperature than during the drier summer months. Measurements at the natural vents were much more variable than those at the steam well, at least partly because of changes in external conditions, such as direction and strength of

the wind. It is difficult to obtain uniform conditions of exposure of the thermometer in the natural vents.

On December 13, 1951, the temperature of the escaping mixture of air and water vapor was measured at several vents in the steaming area just south of Kokoolau crater on the east rift zone of Kilauea. The temperature at the two hottest vents found was 82 and 89.5 C. On December 14 measurements were made of the temperature of the escaping gas at several vents on the Steaming Flat southwest of Sulphur Bank. The temperatures ranged from 71 to 75 C.

Temperature measurements were made on September 9, on the Ohia Lodge flow of 1950 where it crosses the highway in south Kona (Finch and Macdonald, 1953). Many cracks yielded measurements exceeding 130 C at depths of about a foot beneath the surface. Several cracks were found in which the temperature exceeded 230 C, the maximum on the available thermometers. In the hottest cracks dry sticks ignited within 20 seconds, and lead foil lowered to a point 18 inches below the surface melted and dripped in about 5 seconds. Zinc foil softened, but did not melt. Thus the temperature 18 inches below the surface in these hottest cracks, 15 months after the termination of the eruption, still exceeded 327 C, and was probably about 400 C. These hottest cracks are near the banks of the principal feeding river of the flow, in an area where the thickness of the underlying flow is about 50 feet.

RAINFALL RECORDS

Daily readings of rainfall were continued at the gage near the Uwekahuna seismograph station throughout 1951. A new gage was established at the Mauna Loa seismograph station on September 2, 1951, and has been read about every other day since. These readings are on file at the Hawaiian Volcano Observatory. In addition, a gage near the southeastern rim of Halemaumau, and another at an altitude of 5,500 feet on the Mauna Loa truck trail, 2 miles southeast of the Mauna Loa seismograph station, have been read once a month. Monthly totals for these four gages are given in table 10.

TABLE 10.—*Monthly rainfall, in inches, during 1951*

Month	Gage			
	Halemaumau	Uwekahuna seismograph station	Mauna Loa truck trail	Mauna Loa seismograph station
January	7.81	11.43	7.91	----------
February	16.40	18.66	23.35	----------
March	18.35	19.98	19.98	----------
April	1.90	2.11	2.63	----------
May	.83	2.14	1.10	----------
June	1.47	3.18	1.72	----------
July	.76	1.16	.61	----------
August	5.07	8.38	6.37	----------
September	.47	1.83	.61	0.62
October	19.78	19.25	10.91	9.71
November	5.58	8.11	5.37	8.20
December	4.07	3.57	3.42	2.36
Total	82.49	99.80	83.98	----------

VOLCANIC CONDITIONS DURING 1951

General.—There was no eruptive activity of Hawaiian volcanoes during the year 1951. However, seismic activity was decidedly greater than usual. The principal seismic events of the year were the Kilauea earthquake of April 22 and its aftershocks, and the intense Kona earthquake of August 21 and its aftershocks. These earthquake spasms are described in some detail on later pages of this report. Another strong earthquake damaged walls and dishes on November 8.

The earthquake on April 22 apparently accompanied a decrease of magmatic pressure under Kilauea volcano. It was quickly followed, however, by the commencement of rapid northward tilting of the ground at the Whitney Laboratory of Seismology, which is interpreted as indicating a resumption of increasing pressure under Kilauea. During June the apparent increase of pressure beneath Kilauea ceased temporarily, giving way to an apparent increase of pressure under Mauna Loa. In July, however, the pressure increase apparently shifted back to Kilauea. During August, September, and most of October, the rate of ground tilting was about normal for that season. Late in October, however, a sudden northeastward tilting may have been caused by an increase of pressure under both volcanoes. Mauna Loa and Kilauea were uneasy during November and many many small earthquakes originated at Kilauea, and oscillation of tilt suggested fluctuations of pressure beneath Mauna Loa. Uneasiness was less marked during December, and there appears to have been a decrease of pressure beneath Kilauea.

From December 31, 1950, to December 31, 1951, a net accumulation of 9.4 seconds of arc of northward tilt, and 7.2 seconds of eastward tilt was recorded. This suggests that at the end of 1951 the pressure beneath both Kilauea and Mauna Loa was somewhat higher than at the end of 1950.

January.—Mauna Loa and Kilauea volcanoes were very quiet throughout the month of January. Only 18 earthquakes were recorded at the Whitney Laboratory of Seismology, on the northeastern rim of Kilauea caldera, and 8 were recorded at the Mauna Loa station. This was the smallest number recorded at either station for any month since October 1947, when 11 earthquakes were recorded at the Whitney station.

During January ground-surface tilting was mainly southward, following the usual seasonal pattern for that time of year. From January 7 to 17, however, there was a sharp northward tilting of about 2 seconds of arc, suggesting a slight increase of magmatic pressure beneath Kilauea volcano.

Conspicuous steam clouds rose from Halemaumau crater on January 22, following heavy rains. This is a fairly common event and occurs

several times each year. Abundant steam is liberated within Halemaumau about 60 to 90 minutes after the beginning of torrential rainfalls. Although there has been no surface eruptive activity at Kilauea since 1934, the rain water does not have to percolate far beneath the floor of Halemaumau to encounter rock hot enough to evaporate it. The steam issues from numerous small vents on the floor of Halemaumau.

February.—Mauna Loa and Kilauea continued quiet during February. The seismograph at the Whitney Laboratory recorded 25 earthquakes, but only 16 were recorded on the seismograph at the Mauna Loa station. An earthquake felt in the vicinity of Kapapala at 10^h55^m on February 14 originated at a depth of about 7 miles on or near the Kaoiki fault zone near Ainapo, on the southeastern flank of Mauna Loa. At 07^h26^m on February 16 a stronger earthquake was felt from Naalehu to Hilo. It originated about 15 miles below a point on the northeast rift zone of Mauna Loa near Puu Ulaula. Most of the small earthquakes during the month originated in Kilauea volcano.

Tilting of the ground at the northeastern rim of Kilauea caldera continued southward, as is normal during that season of the year. There was almost no accumulation of east-west tilt during the month. However, because there is normally a westward tilting at that time of the year, the absence of tilting may indicate a small increase of magmatic pressure beneath Mauna Loa.

The vents of the 1950 eruption of Mauna Loa were visited on February 9 and 10. Steam was issuing from the vent fissures from an altitude of 10,200 to 11,500 feet, and large amounts of sulfurous fumes were being liberated at an altitude of about 10,000 feet. The vent fissures were still warm, but no heat could be detected in most of the thin flows near the vents. Fume along the southwest rift of Mauna Loa in the vicinity of the 1950 vents was visible from the Hawaiian Volcano Observatory on the afternoon of February 16.

During and after heavy rains in late February spectacular steam clouds rose from Halemaumau, indicating that the principal vent of Kilauea volcano still is very hot a short distance below the surface.

March.—Volcanic quiescence continued throughout March. The seismograph at the Whitney Laboratory of Seismology recorded 27 earthquakes, two more than were recorded in February, and slightly less than the average number recorded per month during times of quiet. Only 14 earthquakes were recorded at the Mauna Loa station.

An earthquake felt from Kilauea caldera to Hilo at 20^h50^m on March 14 had its origin at a depth of about 7 miles on the east rift zone of Kilauea, 5 miles east-northeast of Makaopuhi Crater. At 06^h41^m on March 20 another earthquake was felt by a few persons in the Puueo district of Hilo. This earthquake originated about 6 miles beneath the eastern slope of Mauna Loa, 3 miles east of Kulani cone.

From March 15 to 19 several small earthquakes originated on the western slope of Mauna Loa near Kealakekua, possibly on the same fault involved in the major earthquake of August 21.

Tilting of the ground surface at the northeastern rim of Kilauea caldera continued southward throughout March, as is normal during that season. However, from March 7 to 17 the tilting was distinctly more rapid than normal, indicating a small decrease of magmatic pressure beneath Kilauea caldera. This, like the northward tilting during January, indicates fluctuation of pressure and demonstrates that the magma column beneath Kilauea is still mobile. Slight westward tilting also occurred during the month, as is usual at that season.

April.—The period of volcanic quiescence that began in late December, 1950, was ended on April 22 by a heavy earthquake followed by a swarm of aftershocks. The earthquake and aftershocks are described on later pages. The Hawaiian Volcano Observatory seismographs recorded 132 earthquakes during the month. Of these, 108 were aftershocks of the major earthquake of April 22. The origin of most of the quakes in Kilauea volcano is demonstrated by the fact that 125 of them were recorded on the instruments at the rim of Kilauea caldera, and only 89 of them at the Mauna Loa station.

Although damage to the tiltmeters, caused by the earthquake, made actual measurements impossible, the writers believe that the major earthquake of April 22 accompanied a distinct subsidence of the ground surface at Kilauea caldera, probably caused by a decrease of magmatic pressure at depth. However, this was quickly followed, on April 24, by a fairly rapid tumescence of the volcano, expressed by northward tilting of the ground at the Whitney Laboratory. The northward tilting was considerably in excess of the rate normal for that time of year. It is noteworthy also, that the reversal from southward to northward tilting came nearly a month earlier than usual. Kilauea volcano appeared distinctly uneasy during late April.

May.—The rapid northward tilting of the ground at the Whitney Laboratory, which commenced on April 24, continued throughout May. By the end of the month a total of 6 seconds of arc of northward tilting had accumulated. The rate of northward tilting was about twice as great as normal during that season, and indicated a continued increase of pressure beneath Kilauea. Some cracks on the floor of the caldera and along the Chain of Craters Road opened slightly during the month, possibly in response to the tumescence of the volcanic edifice.

The seismographs of the Hawaiian Volcano Observatory recorded 41 earthquakes during May. Of these, 36 were recorded at the Whitney Laboratory, and 20 at the Mauna Loa station. A feeble earthquake felt by a few persons in the Volcano district (2 to 5 miles

northeast of Kilauea caldera) just after noon on May 17, originated under Kilauea volcano about 6 miles south of the caldera.

June.—The marked northward tilting of the ground at the Whitney Laboratory continued into early June. After June 8, however, the rate of northward tilting decreased to about normal for that season. During late May the rate of eastward tilting had been about normal, but beginning on June 3 it became appreciably greater, and continued above normal for the remainder of the month. This eastward tilting indicated an increase of volcanic pressure beneath the summit area of Mauna Loa.

Forty-two earthquakes were recorded on the Hawaiian Volcano Observatory seismographs during June. Of these, 28 were recorded at the Whitney Laboratory, and 29 at the Mauna Loa station. A series of small earthquakes (mostly tremors) on June 18 and 19, which were recorded only on the Mauna Loa seismograph, indicated some movement on the northeast rift zone of Mauna Loa.

Slight earthquakes were felt by some persons from Kilauea caldera to Hilo at 22^h49^m on June 7 and 08^h32^m on June 11. Both earthquakes had their origin on the east rift zone of Kilauea volcano, the first near Pauahi Crater, and the second about 6 miles southwest of Pahoa.

July.—Seismically, Hawaiian volcanoes were quiet during the month of July. Only 29 earthquakes were recorded on the Hawaiian Volcano Observatory seismographs. Seventeen earthquakes were recorded at the Whitney Laboratory of Seismology, and 15 at the Mauna Loa station. A feeble earthquate at 04^h07^m on July 1 originated on the southwest rift zone of Mauna Loa beneath a point near Sulphur Cone, at an altitude of 11,250 feet. Another, at 23^h20^m on July 5, originated beneath Kilauea caldera, probably within 3 miles of the surface.

Northward tilting of the ground surface at the Whitney Laboratory continued throughout the month, and totaled nearly 4 seconds of arc. That rate of tilting is more than twice the average for that season, and indicated a further increase of magmatic pressure beneath Kilauea volcano. Tilting in the east-west direction showed minor oscillations during the month, but no appreciable net change.

Mokuaweoweo caldera, at the summit of Mauna Loa, was visited on July 25. Small amounts of sulfurous fumes were issuing at the 1940 cinder cone within the caldera, and a little steam was issuing near the northern edge of the 1940 cone, and at places on and near the 1949 cone, both within and just outside of the caldera.

August.—The outstanding event of the month was the severe earthquake that took place at 00^h57^m on August 21. This earthquake, and the damage caused by it, are described in a later chapter. The major

earthquake was followed by a large number of aftershocks. Between 00^h57^m and 24^h00^m on August 21, the seismographs of the Hawaiian Volcano Observatory recorded 135 earthquakes. During this period the seismograph at Konawaena School, in Kona, was not operating, because of extensive damage to the instrument during the major quake. On the basis of the ratio between the number of earthquakes of Kona origin recorded at the Kona and Kilauea stations on later days, it is estimated that if the Kona instrument had been in operation on August 21, it would have recorded about 900 earthquakes during that single day. A woman at Keei, about 5 miles from the epicenter of the major earthquake, felt 109 earthquakes between 00^h57^m and 09^h00^m on August 21. The Kona seismograph recorded 494 earthquakes between the time it was restored to operation, at $15^h 15^m$ on August 23, and midnight on August 31. During August, 264 earthquakes were recorded on the seismograph at the Whitney Laboratory and 268 at the Mauna Loa station. Of these, 235 occurred after the major earthquake of August 21.

The intense earthquake of August 21 probably had its origin on the seaward prolongation of a fault zone that extends into the sea just north of Kealakekua Bay. This fault zone consists of normal faults along which the lower western slope of Mauna Loa has in the past moved downward in relation to the upper part of Mauna Loa east of the faults. It is not known whether the fault movement on August 21 resulted from rise of the summit of Mauna Loa in response to a sudden increase in magmatic pressure beneath it; to a downward elastic rebound of the lower slopes after a longer period bulging of Mauna Loa possibly associated with the 1949 and 1950 eruptions; or to a gravity-impelled downward shifting of the lower, submarine portion of the mountain flank toward the ocean deeps to the west.

At 17^h48^m on August 28 a small earthquake originated beneath the eastern slope of Mauna Loa near Mountain View, and at 18^h04^m on the same day a smaller one originated just east of Kilauea caldera.

Beginning at 06^h02^m on August 23 the seismograph at the Whitney Laboratory recorded 21 minutes of continuous tremor, of the type that indicates subterranean movement of magma. However, there were no other indications of magma movement during the month. Northward and eastward tilting of the ground at the Whitney Laboratory was at a rate about normal for that season.

On August 14, E. K. Field, chief ranger, and Elroy Bohlin, ranger, of Hawaii National Park, flew over the summit of Mauna Loa and observed fumes issuing mildly from the 1940 cinder cone in Mokuaweoweo caldera.

September.—Earthquakes continued abundant during September. Most of the activity centered in the Kona area. The Kona seismograph recorded 471 earthquakes. Most of these were too small and

shallow-seated to be recorded on the seismographs at Kilauea caldera, 42 miles away. During September the seismograph at the Whitney Laboratory recorded 110 earthquakes, and the Mauna Loa seismograph recorded 106.

Most of the earthquakes originated within 10 miles of the Kona seismograph station, probably along the Kealakekua fault zone. However, several had their origins beneath points along the southwest rift zone of Mauna Loa from an altitude of 9,000 feet to the summit, and a few originated in Kilauea volcano. A small quake felt in Hilo at 23^h48^m on September 24 had its focus on the northeast rift of Mauna Loa. From September 23 to 26 several earthquakes originated beneath Hualalai volcano.

On September 16 and 17 about 25 earthquakes originated along the Kaoiki fault zone. This zone of normal faults along the southeastern slope of Mauna Loa is analogous to the Kealakekua fault zone on the western slope. The earthquake of intensity 5, at 01^h43^m on September 16 was felt over most of the southern part of the island. It has already been described on page 146. The quake started rock slides on the walls of Halemaumau that continued at intervals for several days. A crack parallel to the southeastern rim of Halemaumau opened 8 millimeters during the month of September; most of the opening took place during the earthquakes of September 16.

Northeastward tilting of the ground continued throughout September at the Whitney Laboratory. The direction and rate of tilting were about average for that season.

October.—The uneasiness that was manifest at Mauna Loa during September continued throughout October. Earthquakes originated beneath the summit area of the mountain and along the northeast and southwest rift zones, as well as on the Kealakekua fault zone on the western slope and the Kaoiki fault zone on the southeastern slope of the mountain. Starting at 22^h03^m on October 8 the Hawaiian Volcano Observatory seismographs recorded 16 minutes of continuous volcanic tremor, probably caused by subterranean movement of magma. It was followed at 04^h45^m on October 9 by a moderate earthquake that apparently originated at a depth of 25 to 30 miles beneath the summit area of Mauna Loa. This earthquake was felt by some persons throughout the southern part of the island of Hawaii, from Kealakekua in Kona to Hilo. A smaller earthquake at 05^h23^m on the same morning originated deep beneath the upper end of the southwest rift zone of Mauna Loa.

During most of the month the rate of eastward tilting at the Whitney Laboratory was about normal. However, from October 28 to 30 it was much more rapid than usual. The rapid tilt may have been caused by a heavy rainfall that preceded it, or it may have resulted from an increase of magmatic pressure beneath Mauna Loa. Abnor-

mally rapid northward tilting during the same period may have been caused by an increase of pressure beneath Kilauea.

On October 24, I. C. Manus, superintendent of construction and maintenance for the Kulani project, Territorial Department of Institutions, reported a long period of continuous trembling of the ground at the summit of Mauna Loa. This trembling appeared on the seismograms as a series of closely spaced, but separate small earthquakes. Mr. Manus also reported an apparent increase in the amount of steam being liberated at vents within Mokuaweoweo caldera. On October 31 observers in aircraft reported a large cloud of steam rising from the southwest rift of Mauna Loa at an altitude from 8,000 to 12,000 feet. This is the area in which are situated the vents of the 1950 eruption. Fume liberation at the vents has been continuous since the end of the eruption. On October 20, I. J. Castro, acting superintendent, and Elroy Bohlin, ranger, of Hawaii National Park, flew over the summit and southwest rift of Mauna Loa and reported fume (probably largely steam) rising at eight localities along the rift at an altitude from 9,000 to 12,000 feet. The reported increase in the size of the steam cloud on October 31 probably resulted from the heavy rains on October 26–28 coming in contact with still hot lava near the vents, and the clear visibility of the steam owing to the unusually high humidity. The same heavy rains resulted in large and conspicuous steam clouds at Halemaumau, in Kilauea caldera (fig. 38).

During October the seismographs at Kilauea caldera recorded 73 earthquakes, the Mauna Loa station recorded 65, and the Kona station recorded 139.

FIGURE 38.—Clouds of steam rising from Halemaumau on October 29, 1951, following heavy rains on the preceding 2 days. The view is from the Hawaiian Volcano Observatory, at Uwekahuna.

November.—Mauna Loa and Kilauea volcanoes continued somewhat uneasy throughout November. During the month 73 earthquakes were recorded at the Whitney Laboratory. This number is more than twice the average recorded during times of quiescence. The Mauna Loa seismograph recorded 53 earthquakes, and the Kona seismograph recorded 110. The rate of ground tilting during the month was about normal for that season, but moderately strong oscillations of tilt in the east-west direction suggest fluctuations in pressure beneath Mauna Loa.

At 09^h34^m on November 8 an earthquake of intensity 6 in the modified Mercalli scale of 1931 broke dishes and did extensive damage to stone walls at the Kahuku Ranch, 9.5 miles north of the southernmost point of the island of Hawaii. The earthquake was felt over the entire island. It originated on the southwest rift zone of Mauna Loa about 6 miles north of the Kahuku Ranch headquarters, or 15.5 miles north from South Point.

Most of the earthquakes recorded by the Kona seismograph had their origin within a few miles of the instrument, probably largely or entirely on the Kealakeku fault zone. On November 7 at 20^h11^m a small earthquake originated beneath the summit region of Hualalai volcano. On November 21, at 09^h59^m, another small quake originated beneath the Waimea Plain a few miles west from Kamuela, 22 miles northwest of the summit of Mauna Kea. Nearly all the other earthquakes during the month had their origin in Kilauea and Mauna Loa volcanoes.

On the morning of November 23 two observers at different points in the Kona area reported what appeared to them to be smoke near the summit of Mauna Loa. E. K. Field, chief ranger, and R. L. Jeffery, superintendent of construction and maintenance, of Hawaii National Park, were at the summit of Mauna Loa at the time. They reported conditions in the caldera and the adjacent summit area to be normal. The cloud which appeared to the observers in Kona to be smoke apparently was steam rising near the vents of the 1950 lava flows, probably as a result of heavy rains from November 20 to 22.

December.—The uneasiness apparent at Mauna Loa and Kilauea during October and November was much less marked during December. Most of the earthquake activity originated at Kilauea volcano, but the total of 37 earthquakes recorded during the month at the Whitney Laboratory is only slightly more than the average number recorded during times of volcanic quiet. The Mauna Loa seismograph recorded only 21 earthquakes. The Kona seismograph recorded 62 earthquakes during December, bringing the total recorded since August 23 to 1,276. Most of the quakes recorded in Kona apparently originated on the Kealakekua fault zone.

At 20^h19^m on December 6 a strong earthquake was felt over the southeastern part of the island of Hawaii. It originated at a depth of 3 or 4 miles on the east rift zone of Kilauea volcano, about 14 miles east of the caldera. The earthquake had been preceded by 3 days of rapid southward tilting at the Whitney Laboratory, presumably caused by a decrease of magmatic pressure beneath Kilauea caldera. The quake may have reflected a similar decrease of pressure beneath the east rift zone, or it may have been caused by an opening of the rift zone which allowed the subsurface movement of magma away from the caldera, thus reducing the pressure there.

Between December 3 and 7 the ground surface at the Whitney Laboratory, at the northeastern rim of Kilauea caldera, tilted southward through an angle of 4.4 seconds of arc. By December 16 an additional southward tilting of 0.6 second had taken place. A rapid northward tilt of 2.6 seconds of arc followed on December 25. The net southward tilt during the month was 2.2 seconds. This suggests an oscillation, having a net decrease, of pressure beneath Kilauea. Oscillations of the east-west tilt likewise suggest some fluctuation of pressure beneath Mauna Loa.

SPECIAL INVESTIGATIONS

PNEUMATOLYTIC DEPOSITS

White salts deposited by rising gases are common on recent lava flows of Mauna Loa, along the vent fissures and cracks in thick flows. A sample was collected on October 4, 1948, from the vent fissure of the 1942 lava flow at an altitude of 9,300 feet. Another sample of similar material was collected on October 25, 1949, from cracks in the 1949 lava flow on the floor of Mokuaweoweo caldera 0.75 mile east of the 1940 cinder cone. These samples were tested chemically, optically, and by X-ray methods, by Theodore Woodward, of the U. S. Geological Survey. Both samples consisted of thenardite (Na_2SO_4). The SO_4 radical undoubtedly was formed by oxidation of volatile sulfur liberated from the lava. It is uncertain whether the Na radical also was carried out of the lava by escaping volatiles, or was leached out of the lava along the fissures by the sulfuric acid vapors. There is no sign of decomposition of the lava directly associated with the thenardite deposits, but the possibility of decomposition of the lava and leaching of sodium deeper in the fissures cannot be ruled out.

White powdery material collected by R. H. Finch from a crack near Cone Crater, on the southwest rift zone of Kilauea, on September 15, 1947, was determined by Woodward to be opal. Thin crusts of opal, commonly in mammillary and botryoidal forms, are found along many cracks where steam is escaping on the floor of Kilauea caldera.

The associated lavas generally are somewhat decomposed, at least for a few millimeters below the opal crust, and it is probable that the silica was derived by alteration of the lavas by the rising steam. Some transportation of the silica by the rising steam undoubtedly has taken place.

THE KILAUEA EARTHQUAKE OF APRIL 22, 1951, AND ITS AFTERSHOCKS

On April 22, at 14^h52^m Hawaiian time, the southern part of the island of Hawaii experienced the strongest earthquake in this area since 1929, and possibly since 1908. The epicenter of the quake lay just east of Kilauea caldera. The intensity of 5 on the modified Mercalli scale was essentially uniform for 30 miles northeast and southwest of the epicenter, to Hilo and Naalehu respectively. This uniformity of intensity over such a broad area indicates that the origin of the earthquake was at great depth, probably 25 to 30 miles. It was impossible to determine either the epicenter or the depth of origin instrumentally, because all the seismographs of the local net were dismantled by the preliminary waves. The operator of the Hilo seismograph station, Brother Bernard T. Pleimann of St. Joseph's School, reached the dismantled instrument and reassembled it in time to record the coda of the earthquake. Shaking continued on the Hilo instrument for 16 minutes.

The preliminary determination of the epicenter issued by the U. S. Coast and Geodetic Survey on April 24 gives the time at the origin as $00^h52^m21^s$ on April 23, Greenwich civil time, and the magnitude on the Gutenberg-Richter scale as 6.5 as determined at Pasadena, Calif., and 6.0 at Berkeley.

The earthquake was felt generally over the entire island of Hawaii, and by many persons on the islands of Maui and Oahu. Damage resulting from the quake was slight. On the southern part of the island of Hawaii many small objects were overturned, and some dishes were broken. Many, but not all pendulum clocks were stopped. A water pipe was broken at the Hawaiian Volcano Observatory, and a plate-glass window at Glenwood was cracked. Water slopped over the rims of some tanks. Small earth slips occurred in road cuts between Kilauea caldera and Hilo, and north of Hilo along the Hamakua coast. Several rock slides occurred on the walls of Kilauea caldera, and many occurred on the unstable walls of Halemaumau crater. The latter were small. No large blocks of the crater rim were displaced, although many cracks near the rim were appreciably widened. The crack which crosses the tourist area at the southeastern rim of the crater opened 6 millimeters at the time of the earthquake, and 3 millimeters more during the period of aftershocks.

Small slides continued in Halemaumau for about a week after the main earthquakes. Small rock avalanches occurred on the walls of Alae and Makaopuhi craters, on the east rift zone of Kilauea. Superintendent F. R. Oberhansley of Hawaii National Park reported rock falls at the cliffs of Hilina Pali and Puu Kapukapu, at the southern shore of the island. Minor cracking of the highway occurred at the

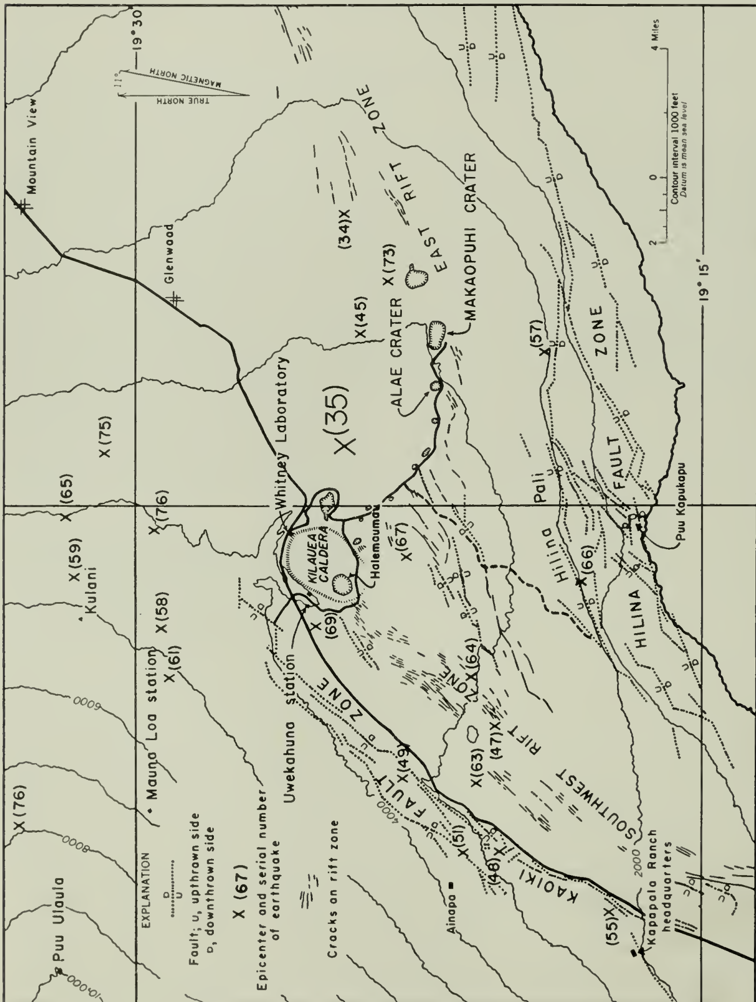

FIGURE 39.—Map of Kilauea caldera and vicinity, showing the epicenters of the large earthquake of April 22 and its aftershocks in relation to fault zones and the rift zones of Kilauea volcano. The position of the epicenter of the large earthquake (number 35) was estimated on noninstrumental grounds and its location is only approximate.

northeastern rim of Kilauea caldera, a quarter of a mile southeast of the Whitney Laboratory (fig. 39), apparently caused by settling of a thin fill under the pavement when the block at the edge of the caldera moved slightly toward the caldera. Cracking in the soil also was observed at several places north and east of Kilauea caldera, apparently caused by lurching of the soil. No surface faulting was observed.

The Bosch-Omori seismograph at the Whitney Laboratory on the northeastern rim of Kilauea caldera (fig. 39), and the vertical seismograph at Uwekahuna, were dismantled. The vertical seismograph was restored to operation at $15^h\ 20^m$, but resumption of recording on the Bosch-Omori seismograph was delayed until $16^h\ 45^m$ by electric-power failure caused by the earthquake. The wire suspensions on the heavy mass of one component of the Hawaiian-type seismograph at the Mauna Loa station were broken, and the mass, weighing 220 pounds, dropped to the floor of the vault, 3 feet from its proper position. At the Uwekahuna vault the wire suspensions on both components of a semiportable tiltmeter were broken and the horizontal pendulums, each weighing 35 pounds, dropped onto the pier. The breaking of the wire suspensions, which have considerable strength under normal conditions of lateral swing of the pendulums, suggests a vertical dancing of the pendulums. This damage and the dismantling of the vertical seismograph, which is seldom dismantled even by strong earthquakes, indicate a high angle of emergence of the earthquake vibrations, consonant with a deep origin nearly beneath Kilauea caldera.

Damage to the seismographs and tiltmeters made it impossible to determine with certainty the direction of tilt during the earthquake, but it probably was southeastward at the Whitney station and eastward at Uwekahuna. The direction of first motion of the earthquake was south and east at the Whitney station, and down at the vertical seismograph at Uwekahuna. The writers believe that the earthquake accompanied a marked subsidence at Kilauea, probably caused by a decrease of volcanic pressure at depth. Subsidence is suggested by the direction of first motion and the probable direction of tilt, and also by the observed generalization that the strongest local earthquakes generally, if not always, accompany subsidence rather than tumescence. It was observed that the subsidence was immediately followed by the beginning of rapid northward tilting of the ground at the Whitney station, apparently indicating restoration of the pressure. This rapid northward tilting continued until June 8.

The major earthquake was preceded, at $04^h\ 53^m\ 53^s$ H. s. t. on April 22, by a moderate earthquake which originated at a depth of about 21 miles on the east rift zone of Kilauea volcano, 10 miles east of the caldera (location 34, fig. 39).

During the 7 days following the major shock 108 earthquakes were recorded on the Hawaiian Volcano Observatory seismographs. Of this number, 71 occurred on April 22 and 23. More than half were tremors, too small to permit identification of separate phases in the record. Figure 40 is a graph of daily seismicity from April 20 to 30, derived by assigning a numerical value to each earthquake, depending on its intensity, and totaling these values for each day (see page 184).

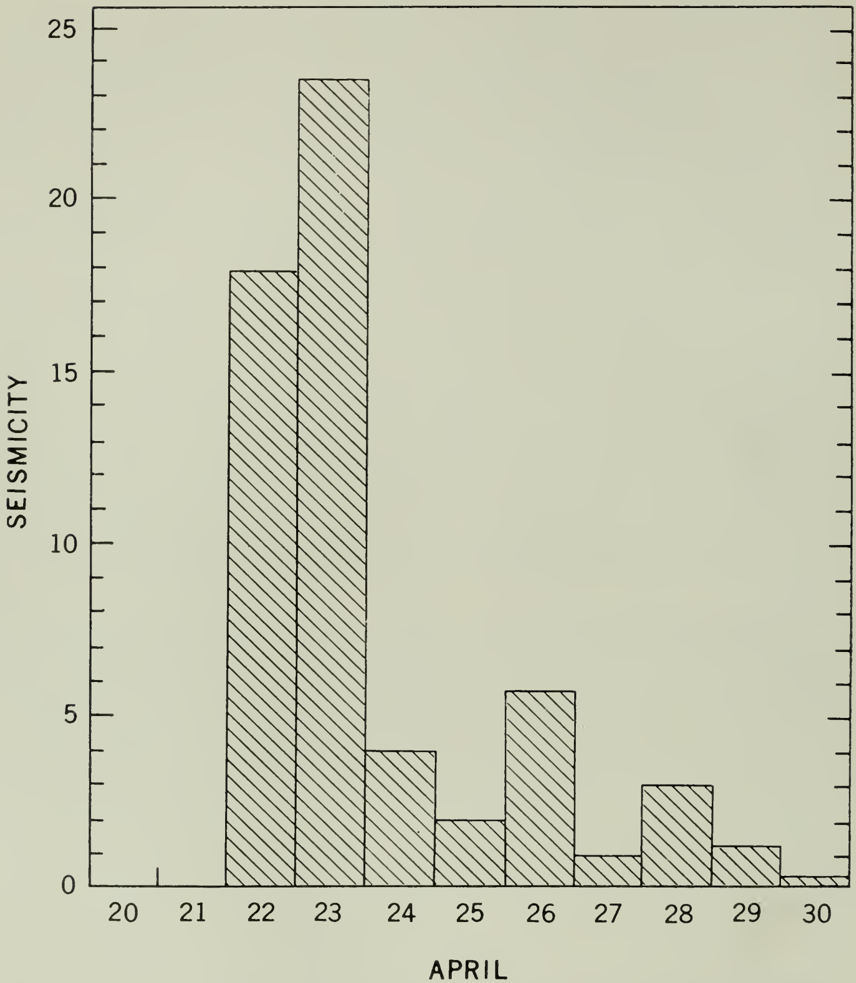

FIGURE 40.—Graph showing daily seismicity at the Whitney Laboratory of Seismology from April 20 to 30, 1951.

All earthquakes producing a double amplitude of oscillation of more than 60 millimeters on the Bosch-Omori seismograph are classified as strong, and receive the same seismicity rating. Thus the major earthquake of April 22 received the same seismicity value as the much smaller "strong" earthquakes which took place on April 23 and 26. If allowance were made for this, the seismicity on April 22 should be somewhat increased. The high seismicity on April 22 and 23 results principally from the large number of very small aftershocks (tremors and very feeble earthquakes) on those days.

Most of the aftershocks were too small to be located. The phase arrivals were not recognizable on the seismograms, or recognizable only on the record of one station. Nineteen could be located with

reasonable certainty. The epicenters of these are shown in figure 40, in which the number accompanying the cross indicating the epicenter is the serial number of the earthquake for the current year. The date, time, and intensity are given following its serial number in table 4. All the located aftershocks were of comparatively shallow origin. The deepest was that at 03^h 57^m on April 26 (serial No. 73), at a depth of about 11 miles on the east rift zone of Kilauea. Most of the others originated at depths ranging from 3 to 8 miles. The aftershocks generally fall into two groups, one distributed along the rift zones of Kilauea volcano, and the other associated with the Kaoiki fault zone along the southeastern slope of Mauna Loa and the prolongation of the Kaoiki zone northeastward beyond any recognized surface fault offsets. It is of interest to note that the northeastward continuation of the Kaoiki fault was suggested years ago by H. O. Wood (1915, p. 56–57), who also found an apparent clustering of earthquakes along this line. The Kaoiki fault zone lies at or near the surface contact between Kilauea and Mauna Loa volcanoes, and earthquake activity along this zone probably resulted from relative downward movement of Kilauea along the Kaoiki faults in response to decrease of volcanic pressure beneath Kilauea.

Many of the small aftershocks which could not be definitely located apparently originated beneath Kilauea caldera or along one of the rift zones in the immediate vicinity of the caldera. Two of the quakes originated along the Hilina fault zone near the southern coast of Kilauea.

THE KONA EARTHQUAKE OF AUGUST 21, 1951, AND ITS AFTERSHOCKS

Small to moderate-sized earthquakes associated with the volcanoes Kilauea and Mauna Loa are numerous, but strong earthquakes are comparatively rare in the Hawaiian Islands. The earthquake of August 21 ranks among the strongest on record in the Hawaiian region, and probably was the strongest since 1868, when severe earthquakes did extensive damage throughout the southwestern part of the island of Hawaii.

The earthquake of August 21, 1951, had its origin a few miles west of the western shoreline of the island, and caused much damage in the adjacent district of central Kona. In consequence, it has become generally known as the "Kona earthquake" (Macdonald and Wentworth, 1951, 1952; Wentworth, 1951, 1953). The quake was felt strongly over the entire island of Hawaii, and weakly by many persons on the islands of Maui and Molokai, and in Honolulu, on the island of Oahu, 180 miles from the focus of the earthquake. The principal earthquake was followed by many aftershocks, of lesser intensity.

NARRATIVE OF THE EARTHQUAKE

At 57 minutes past midnight on August 21, residents of the island of Hawaii were awakened by a violent earthquake. The violence was greatest in central Kona, from Kealakekua to Hookena (fig. 41). Near

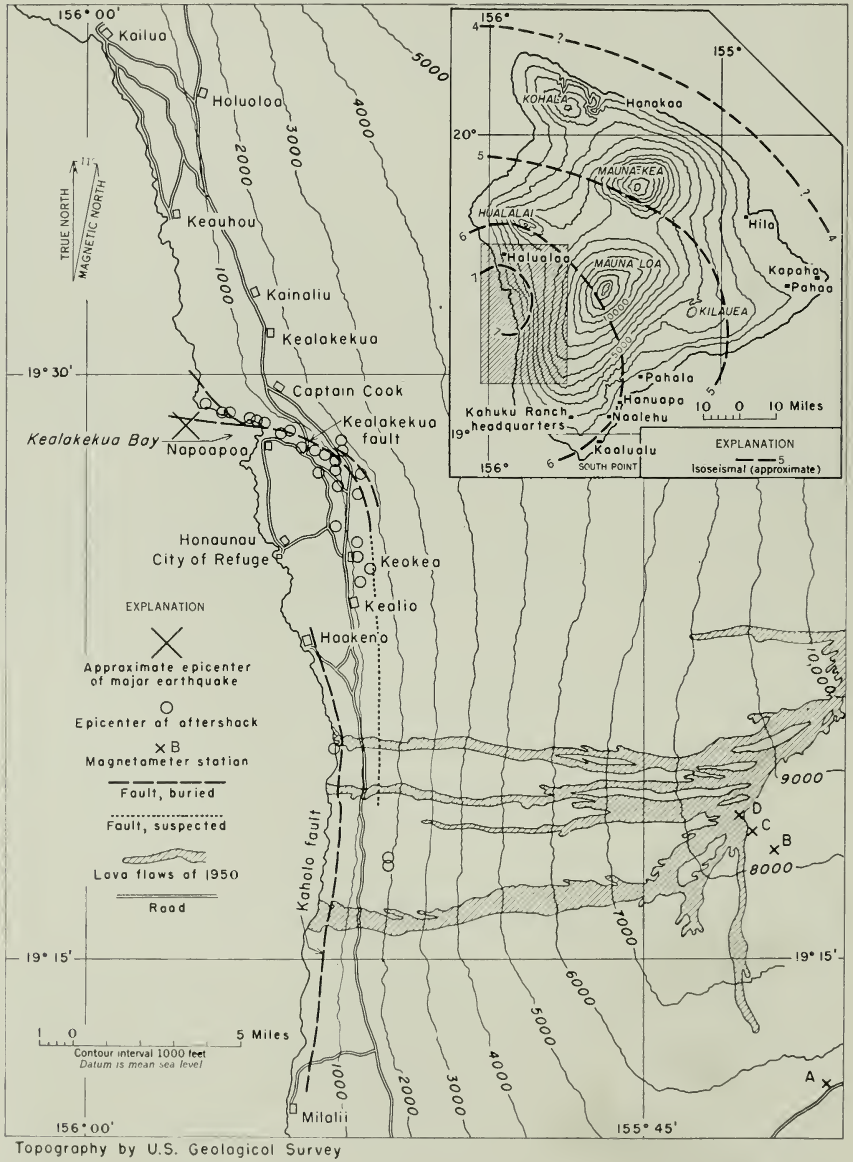

FIGURE 41.—Map of the central Kona district showing the location of places mentioned in the text, and the approximate locations of the epicenters of the major earthquake of August 21, 1951, and the aftershocks for which reasonably good locations were obtained. The inset map of the island of Hawaii shows the location of the area (shaded) covered by the other map, and the approximate position of the isoseismal lines for the major earthquake.

the epicenter the initial movement was reported to be largely up and down, with some swaying in an east-west direction. This swaying rapidly increased in intensity, and changed to what appeared to several persons to be a vortical motion. A few persons, who were awake at the time the earthquake occurred, report that the apparent shaking of the ground was preceded by a dull roar which seemed to come from the ground. Observers near the epicenter reported the shaking was nearly continuous for an hour or more after the major quake.

Noise during the major earthquake was intense. Dishes, furniture, and canned and bottled goods crashed to the floor, doors and windows rattled, water tanks collapsed, rocks rolled from stone walls and banks, and landslides and rock falls rushed down cliffs.

Within moments, several houses, churches, and a school building were partly or entirely destroyed, and many other houses slightly damaged. About 200 water tanks collapsed, miles of stone wall were thrown down, roads partly blocked by rock slides, and road pavements and shoulders badly cracked. Headstones in cemeteries were shifted or overturned, water lines broken, and telephone and electric service disrupted. Fortunately, only two small fires broke out, and only two persons received minor injuries from broken glass. One of the most serious consequences of the earthquake was the loss of water supply throughout much of the central Kona district.

The greatest destruction occurred in the 10-mile interval south of the village of Captain Cook. However, minor damage extended from Holualoa, 10 miles north of the epicenter, to Pahala, 37 miles southeast. As far away as Naalehu (fig. 41), many dishes fell to the floor in homes, groceries and bottles toppled from shelves in stores, and stone walls collapsed. One house was shifted several inches off its foundation. In the vicinity of Kilauea caldera, 45 miles from the epicenter, a few objects were toppled from shelves, pavements were cracked, and many landslides were started.

Macdonald was driving through Naalehu, 36 miles from the epicenter, when the earthquake occurred. The car swerved violently, as though it had struck deep mud on the road. Immediately afterward dead branches snapped from trees overhead and fell on the pavement. Suspended signs and electric wires swung violently, the few visible lights went out, and blue sparks from broken wires were observed.

At Kealakekua Bay large rock slides were started on the cliff at the head of the bay. At Napoopoo, on the southern shore, the ocean water was observed withdrawing from shore, and most of the inhabitants of the village were quickly evacuated to higher ground in fear of a large tsunami, or "tidal wave." A flood of water entering one basement from a collapsed water tank added to the confusion. Actually, a tsunami did occur, but was too small to cause any damage.

Two small fires broke out as a result of the earthquake. Kerosene spilled in the kerosene-power refrigerator caused one fire in south Kona. The other was in Naalehu, where the earthquake upset a lighted kerosene lamp. But fires were quickly extinguished. The only human casualities were in the same house. Mr. and Mrs. W. H. Thompson suffered cuts on their feet from broken glass on the kitchen floor, while extinguishing the fire started by the refrigerator.

Responsible persons at Naalehu and Pahala reported bright flashes of white light at the time of the major earthquake. These persons believe the flashes were not the result of electric sparks caused by broken circuits. The flashes observed by Macdonald at Naalehu, caused by electric sparks, were distinctly blue rather than white. Peculiar lights have been reported during some other strong earthquakes.

During the night of August 21, shortly after the major earthquake, persons in the central Kona area reported a distinct odor of hydrogen sulfide, apparently coming in intermittent waves. The source of that odor is not known. No increase in liberation of fumes was detected by aerial observers at the vents of the 1950 lava flows on the southwest rift of Mauna Loa.

The main earthquake was followed by a large number of aftershocks. The exact number will never be known, because the seismograph at Konawaena School was badly damaged by the preliminary waves and many of the aftershocks were too small to be recorded at the stations at Kilauea caldera or at the Mauna Loa station. Mrs. H. Masuhara, at Keei, just south of the Keelakekua fault and 5 miles east of the epicenter of the major earthquake (fig. 41), counted 109 earthquakes between the time of the principal shock and 9 o'clock the next morning. Between the time of the main earthquake and $15^{h}15^{m}$, on August 23, when the Konawaena seismograph was restored to operation, the Bosch-Omori seismograph at the northeastern edge of Kilauea caldera recorded 171 earthquakes. This record was only a small proportion of the number that would have been recorded by the Konawaena instrument if it had been in operation. The Konawaena seismograph recorded 90 earthquakes the first 24 hours after it resumed operation, and by midnight on August 31 had recorded 494 aftershocks. Most of these were too small to be felt, even near the epicenter. Nevertheless, aftershocks sufficiently large to be felt were so numerous that the people of Kona were apprehensive for several weeks, and on August 22 it was deemed advisable to hold graduation ceremonies at the Konawaena School out of doors instead of in the auditorium.

INSTRUMENTAL DATA

THE MAJOR EARTHQUAKE

The principal earthquake dismantled all seismographs on the island of Hawaii. All but the Bosch-Omori seismograph in the Whitney

Laboratory on the northeast rim of Kilauea caldera were dismantled by the preliminary waves. Precise time control, and consequently the precise time of arrival of the first waves, is lacking on the Kona and Hilo instruments. Consequently instrumental data are inadequate for the close location of the focus of the earthquake. The interval between the arrival of the primary and secondary waves on the north-south component of the Bosch-Omori instrument was 9.5 seconds, corresponding with a distance from the Whitney Laboratory to the origin of the quake of about 47 miles.

John C. Forbes, instrument-maker at the Hawaiian Volcano Observatory, repaired the minor damage to the Bosch-Omori seismograph and restored it to operation at 01^h24^m, 27 minutes after the earthquake started. At that time the instrument was recording the long waves of a large earthquake. The period of these waves ranged from about 6 to 8 seconds and averaged about 6.7 seconds. Their double amplitude ranged up to 67 millimeters, corresponding to a theoretical ground displacement of about half a millimeter. These waves continued with gradually decreasing amplitude until 03^h20^m a. m. Because no other earthquake at an appropriate time was observed by more distant stations, these long-period waves probably were surface waves of the major Kona earthquake.

The time of origin of the major earthquake is given in the notice of preliminary determination of epicenter issued by the U. S. Coast and Geodetic Survey as $00^h56^m57.5^s$ Hawaiian standard time ($10^h56^m57.5^s$ Greenwich civil time). The time of beginning of registration of the preliminary waves at the Whitney Laboratory at Kilauea was $00^h57^m09.5^s$ Hawaiian standard time.

The direction of the first ground movement at Kilauea caldera was east-southeast and up, that at the Mauna Loa station was east-northeast, and that at the Kealakekua station, was east-northeast. At the Kealakekua station the north-south component of the seismograph suffered only minor damage, but the suspensions of the east-west component were broken and the weight dropped on the floor 2 feet west of the pier.

THE AFTERSHOCKS

The Kona seismograph, at Konawaena School (fig. 41) was restored to operation at 15^h15^m on August 23. Before that time location of the points of origin of the aftershocks on an instrumental basis was uncertain, because of the very short base of the triangle formed by the intersection of lines from the earthquake foci to the other stations. Earthquakes after that time are fairly well located because of the control given by the Kealakekua seismograph. Most of these aftershocks were located by means of data from four stations: Kealakekua, Mauna Loa, Hilo, and Whitney (Kilauea).

Locations of the epicenters of some of the aftershocks which occurred after 15^h15^m on August 23 are shown in figure 41. Thirty-three such aftershocks have been located with small probable error. Most of them fall on or near a fault that extends into the sea in a west-northwesterly direction along the northern edge of Kealakekua Bay. The existence of this fault, partly buried by subsequent lava flows, has been recognized for many years (Dana, 1890, p. 30; Stearns and Macdonald, 1946, p. 37, pl. 1). At its eastern end it bends southward, and the writers believe that the abnormally steep lower western slope of Mauna Loa inland from the highway for 15 miles or more south of Captain Cook, is a fault scarp deeply buried by later flows. An interesting partial confirmation of this theory is furnished by the location of the epicenters of several aftershocks along this line (fig. 41).

Especially strong aftershocks occurred at 01^h28^m, 09^h56^m, 10^h12^m, 18^h32^m, and 22^h48^m (Hawaiian standard time) on August 21; and at 17^h15^m on August 22. Slightly less strong quakes occurred at 2^h14^m and 6^h28^m on August 22.

The frequency of aftershocks decreased rapidly from August 23 to September 4. As shown in figure 42, the average frequency then

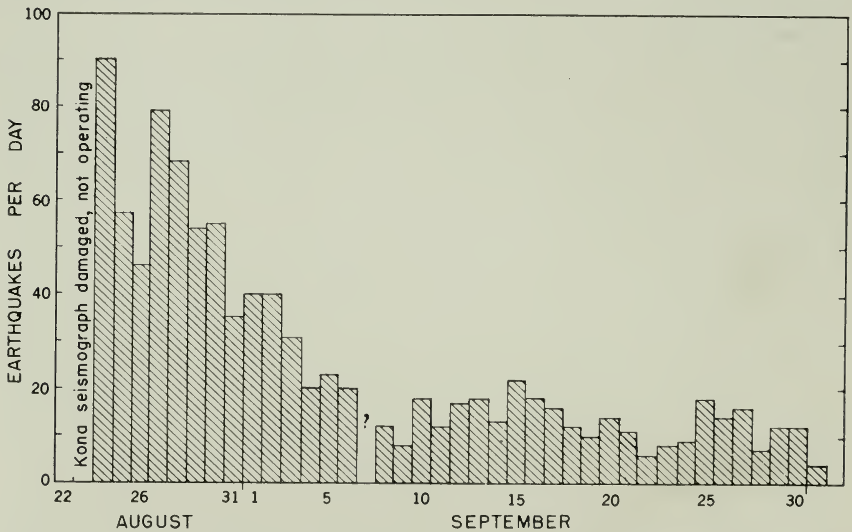

FIGURE 42.—Graph showing the frequency of aftershocks of the earthquake of August 21, to the end of September 1951.

decreased very slowly until the end of September. No data are available for September 7, because of mechanical failure in the recorder at the Konawaena station.

Table 11 shows the gradual decrease in the number of earthquakes recorded on the Konawaena seismograph from the time of the major earthquake to the end of the year.

TABLE 11.—*Number of earthquakes recorded on the seismograph at Konawaena School from August 23 to December 31, 1951*

Period	Number of earthquakes recorded	Average number per day
August 23-31	494	61.0
September	471	15.7
October	135	4.5
November	109	3.6
December	62	2.0
Total	1,271	

From the time the instrument was restored to operation until the end of August, the Kealakekua seismograph recorded 494 earthquakes, and by the end of September had recorded 965. Nearly all are regarded as aftershocks of the major earthquake of August 21. Most were too small and shallow-seated to be recorded at the other stations, and hence their foci could not be closely located. Probably most originated along the Kealakekua fault at the northern edge of the Kealakekua embayment. The apparent depth of origin of the located aftershocks ranged from 3 to 12 miles, most of them about 6 or 7 miles. No progressive change of depth with passage of time is apparent.

EFFECTS OF THE EARTHQUAKE

TOPOGRAPHIC AND GEOLOGIC SETTING

The area in which the earthquake originated, and in which the effects were strongest, lies on the western slope of Mauna Loa volcano. The main highway traverses it from north to south, at altitudes of 1,000 to 1,300 feet, and side roads lead to the seacoast at Napoopoo, Honaunau, Hookena, and Milolii (fig. 41).

Most of the terrane is an initial constructional surface formed by lava flows from the summit and southwest rift zone of Mauna Loa, and is essentially untouched by erosion. Low sea cliffs cut by wave action border much of the coast. The average westward slope is approximately 7°, or about 650 feet to the mile.

At the northern side of Kealakekua Bay a fault scarp, in large part mantled by later lava flows, extends inland in a southeasterly direction. This fault has been named the Kealakekua fault (Stearns and Macdonald, 1946, p. 37). It apparently consists not of a single fracture, but of a series of fractures en echelon. About 5 miles southeast of Kealakekua Bay the scarp bends southward, and becomes less distinct. However, for more than 10 miles southward there is a narrow zone near the highway in which the surface and the surficial lava flows slope westward at an angle of about 10°. Above, and at many places below this steep zone, the slope decreases to about 7°. The writers believe that this steep zone is the surficial expression of a zone of fault-

ing deeply buried by later lava flows. The occurrence of several well-located aftershocks of the August 21 earthquake along this zone lends confirmation to this theory.

One branch of the Kealakekua fault bends northwestward at the northern edge of Kealakekua Bay, and is responsible for the cliff, known as Pali Kapu o Keoua, at the head of the Kaawaloa peninsula, just north of the bay (Stearns and Macdonald, 1946, p. 37). There is little doubt, however, that another branch extends nearly westward beneath the ocean. Its position is clearly marked by indentations in the 500- and 1,000-fathom submarine contours. The hypocenter of the Kona earthquake of August 21 probably was on this westward continuation of the Kealakekua fault.

Near the shore, from Hookena to Milolii, another line of cliffs mantled with younger lava flows apparently is also a fault scarp. This has been called the Kaholo fault (Stearns and Macdonald, 1946, p. 37, 39). A few of the aftershocks of the Kona earthquake probably were associated with this fault.

The steep seaward slope of the entire Kona area results in a distinct asymmetry to the terrane, and that asymmetry of necessity extends to nearly all structures on the terrane. Buildings rest on foundations that are high on one side and low on the other. Roads in many places rest on a cut on one side and fill on the other, or on a fill that has one thin side and the other thick. Stone walls parallel to the coast have a higher side in the downhill direction. This results in a lesser degree of stability than in structures built on flat terranes, and in a favored direction of unstability. Partly because of the higher foundations and thicker fills on the seaward side, and partly because of the continuous effect of gravity, structures tended to move down hill during the earthquake regardless of the direction of the actual shaking. This effect must be kept in mind in using the direction of displacement of objects in locating the epicenter.

ROCK SLIDES

The Kona earthquake caused many small rock slides in highway cuts. Most of them came from cuts on the inland side of the highway, probably because the cuts were higher on that side. Most of the slides were small, bringing down blocks less than 2 feet across. These caused little damage and were easily removed. A few larger slides brought down blocks weighing several tons, the removal of which required the use of bulldozers or other heavy equipment. The large slide farthest from the origin of the earthquake occurred at a high road cut just west of Honuapo, 40 miles from the epicenter. Small slides and rock falls in road cuts extended as far as Kilauea caldera, 44 miles from the epicenter. Many small rock avalanches took place

in Halemaumau crater during, and for several days after, the earthquake.

Many large slides took place on the fault scarp (Pali Kapu o Keoua) at the northern edge of Kealakekua Bay. The slides caused a disturbance of the water of the bay just after the earthquake. Many residents fled inland from the coastal village of Napoopoo, fearing a big tsunami ("tidal wave"). Slides continued on the Napoopoo cliff for several days after the earthquake, sending up clouds of yellowish-brown dust, leaving fresh scars on the cliff face, and building talus fans at the foot of the cliff.

Less numerous and smaller slides also occurred along the Kaholo cliff just inland from the village of Hookena Beach, where many fragments of the lava veneer were dislodged during the earthquake.

A large part of the damage to road cuts did not result from land slides. Most of it was caused by loose or semiloose material rolling down the slope and fraying the banks. Few of the highway cuts exceeded 5 feet in height, or were dressed back to any approximation of an equilibrium slope. The earthquake of August 21 greatly exceeded in size any previous quake in the affected area since the road cuts were made, and dislodged much of the loose material and allowed it to roll onto the road.

The distribution of abundance of rock slides in road cuts is shown in figure 43, in which it is represented by the portion of the columns labeled "bank caving." Like the other damage shown in the graph,

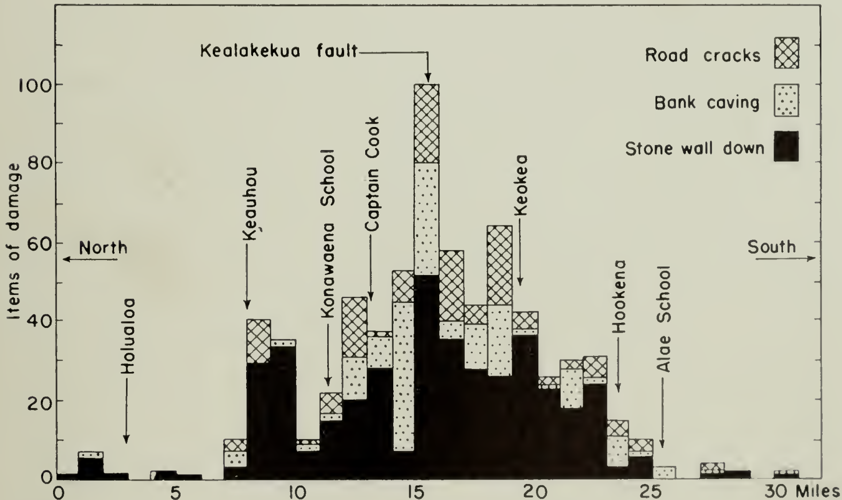

FIGURE 43.—Diagram showing the frequency distribution of three of the principal types of earthquake damage along the main highway. The arrows indicate the position on the highway of some villages and other features. Note the centering of damage near the Kealakekua fault.

it was greatest in the immediate vicinity of the Kealakekua fault, inland and a little south of Kealakekua Bay.

TSUNAMI

The earthquake was accompanied by a small tsunami, or "tidal wave." At Napoopoo wharf the water withdrew from shore. The tide was low at the time, and withdrawal of the water lowered the level to about 4 feet below normal low tide. Immediately afterward the water returned shoreward, and the level rose about 2 feet above low tide.

At Milolii, Eugene Kaupiko reported that a few minutes after the earthquake, which he felt in a canoe anchored offshore, the water receded from shore, revealing the sea bottom as far out as the edge of the wharf. This represents a lowering of the water level about 3 feet. Following the withdrawal, the water returned shoreward causing a rise of the water level 3 or 4 feet above normal low tide and floating away a canoe which had been drawn up on the beach about 2.5 feet above high-tide level. One large fall and rise of the water level was apparently followed by many small oscillations.

At Honaunau, between Napoopoo and Milolii, Eli Cooper, the caretaker of the City of Refuge park, observed the water's edge a few minutes after the earthquake. He could see no signs of disturbance of the water, but a small tsunami could have occurred between the time of the earthquake and when he reached the strand. At Hookena no tsunami was observed, and there was none large enough to flood the floor of the dock, about 4 feet above normal water level. However, it cannot be said definitely that no small tsunami occurred.

The Honolulu tide-gage record shows a distinct oscillatory disturbance of the water starting at approximately $01^h\ 35^m$, 38 minutes after the earthquake. Seven or more oscillations are detectable, having an average period of about 14 minutes, and reaching an amplitude from crest to trough of 3.6 inches. This undoubtedly is the record of a seiche set up in Honolulu harbor by the tsunami. Using the time of beginning of the disturbance at Honolulu as that of arrival of the tsunami, the average speed of travel of the tsunami from the epicenter to Honolulu was about 284 miles an hour. The time of beginning of the disturbance at Honolulu corresponds with the calculated theoretical arrival time of a tsunami caused by the Kona earthquake, so there can be little doubt the disturbance was of that origin. A similar disturbance is shown on the record of the Hilo tide gage. The time of beginning of the disturbance at Hilo is less definite, but apparently was about $02^h\ 38^m$. This corresponds with a much slower average speed of travel of the tsunami, of about 78 miles an hour, as the waves were refracted around the island in comparatively shallow water.

DAMAGE TO BUILDINGS

Shortly after the earthquake the Kona police estimated that about 200 homes in the area had suffered some degree of damage. Most houses in the area near the epicenter are of frame construction, set on knee-braced timber underpinnings. Such supports proved capable of undergoing the shaking and distortion caused by the earthquake without sustaining serious damage. Most of the damage was minor and quickly repaired. Some houses shifted from a fraction of an inch to 3 or 4 inches on their foundations. Many were sufficiently twisted to make it difficult or impossible to close windows and doors. In nearly all houses dishes and other objects were thrown from shelves. Only the more seriously damaged structures are enumerated below.

At Kaimalino, 0.3 miles south of Kealia (fig. 41), a shop building collapsed. This building was placed on timber supports level with the highway at the front, but 6 feet above ground level at the back, without adequate cross-bracing. Failure of the underpinning allowed the building to tilt backward and slump to the ground. A similar situation existed at Keokea, 1.2 miles north of Kealia, where a service-station building slumped down hill from the highway and partly collapsed.

In the Kahauloa area, about 1.7 miles east of Napoopoo village, the walls of a store partly collapsed, as result of distortion caused by shifting on its foundation. The warehouse of another store was badly damaged.

At Hookena beach two old frame houses were destroyed. The first, which had been occupied briefly in 1889 by Robert Louis Stevenson, collapsed when its timber underpinning failed. The second one also was dropped onto the ground by failure of its underpinning and apparently dropped almost straight downward. This building was somewhat twisted, but not otherwise seriously damaged. At Kealia, and Kiilae, about 0.4 mile south of Kealia, two other frame houses were badly damaged by collapse of their timber underpinning. All these examples of damage to frame houses appear to have been caused by inadequate cross-bracing or poor materials in the underpinning, in some instances probably aggravated by insecure footings.

Structural damage most distant from the epicenter occurred at Naalehu, 36 miles southeast of Napoopoo. Wallboard in a restaurant was cracked and one house was moved several inches off its foundation.

A striking example of the effect of poorly designed underpinning is furnished by the Honaunau School. This school was a long, narrow frame building placed with its length parallel to the contour of the ground surface. The front of the building was about 3 feet above ground level and the back about 10 feet above ground. It was supported on timber posts. The posts and the knee-bracing parallel to

the length of the building were entirely adequate, but there was comparatively little bracing parallel to the width of the building, and some of this bracing was fastened, not to joists, but to floorboards. As a result, the underpinning was deficient in stiffness parallel to the ground slope. The direction of shaking during the earthquake was nearly parallel to this weakness in the structure, and the swaying caused the underpinning to fail in part and allow the building to slump downhill onto the ground (fig. 44). The building is a total loss.

FIGURE 44.—Honaunau School building from the southwest. All but the south end of this building was dropped and moved westward owing to inadequate bracing of the underpinning in an east-west trending direction transverse to the longer dimension. The wood-stave water tank collapsed and was thrown westward from its concrete-block footings.

Several church buildings in the area near the epicenter were constructed with masonry walls. Most of these walls suffered some cracking, and others were seriously damaged. The masonry consists of fragments of lava rock laid with mortar made by calcining coral limestone. In some there was very little mortar in the inside parts of the wall. Most of the buildings were more than 95 years old.

In the Central Kona Church at Kealakekua, interior plaster on the eastern and western walls was cracked, but the masonry showed little or no cracking. At the back of the church is a small lean-to addition, the roof of which is supported by beams with one end set into niches in the wall of the main building. During the earthquake there was

enough differential movement of the two parts of the building to pull the beams out of their supporting niches and allow the roof of the addition to drop a few inches. At the front of the church is a tower covered with exterior plaster. The tower and main church buildings are essentially separate structures, and apparently moved independently during the earthquate. The plaster of the tower was badly cracked.

St. Paul's Church at Honalo, 1.9 miles north of Kealakekua, suffered severe cracking of the masonry, in the main building and in the rectory. Kahikolu Church, at Napoopoo, suffered little damage. The lintels and interior plaster showed some cracking, but the masonry was not damaged.

The Pukaana Church at Hookena Beach was bady damaged. The building consisted of masonry walls, and a sheet-iron roof supported on heavy hand-hewn beams. These were supported by east-west beams resting in niches on the upper edge of the front and back walls. During the earthquake most of the front (west) wall was thrown out, some debris falling as much as 25 feet from the building. The other walls were not appreciably damaged, even the interior plaster showing little cracking. It is possible that during the quake the roof may have moved as a separate unit from the rest of the structure, and by its tendency to lag during the initial violent eastward movement of the ground may have pushed the front wall out.

A small stone building nearby, which had long been without a roof as shown by trees growing within the walls, similarly had the end walls thrown outward, to west and east, while the side walls remained standing though somewhat cracked.

The church 0.6 mile north of Hookena Beach was heavily damaged. The upper portions of the eastern and western walls were thrown down (fig. 45) and the interior plaster was cracked. However, the walls were built of loose stones laid together, without mortar between them except near the faces, where the interior and exterior plaster had penetrated a short distance. Considering the type of construction, probably the most surprising feature is that the building had not collapsed previously, in one of the strong earthquakes that occur in Kona every few years.

The lessons to be learned from the structural damage caused by the earthquake are those which have been taught by many strong earthquakes elsewhere. A large proportion of the damage results from poor construction, or inappropriate materials. Masonry structures that are not reinforced are inadvisable in any area subject to strong earthquakes. Footings should be firm, and construction materials, particularly the underpinning, should be sound. Cross-bracing, particularly of underpinning, should be adequate in all directions. The best insurance against earthquake damage is sound construction.

DAMAGE TO WATER TANKS

Most dwellings and public buildings in the Kona area are equipped with water tanks for storage of rain caught on the roof. In addition there are many tanks used to store water for cattle. Nearly all

FIGURE 45.—Church at Puaa, 0.6 mile north of Hookena, viewed from the northwest. The western and eastern walls of the building were damaged. The severe damage at the northwest corner of the church building and of the old unroofed building beyond it, suggest displacement of the walls toward the northwest in the direction of the epicenter.

these tanks are of wooden-stave construction. Many of these round tub-type tanks were destroyed or damaged by the earthquake. The few metal and reinforced masonry tanks were undamaged. Because

of their importance, not only in Kona but in many other Hawaiian communities, a special study of the damage to tanks by the earthquake was undertaken.

About 200 tanks, of a total probably exceeding 2,000 in the heavily shaken area, were damaged or destroyed by the earthquake. Tank damage extended from Keauhou at the north to Milolii on the south, and was most severe in the area from Captain Cook to Hookena. Tanks showed all degrees of failure, from the development of slight leaks to complete collapse. Of 90 tanks for which complete data have been compiled, 43 were reported demolished or totally destroyed. Of the remainder, several had the bottom collapsed, others developed general leakage that cause loss of all the water, and many were so dislodged and deformed that complete rebuilding was necessary. Broken pipe-fittings released all the water at some tanks, but they were repaired without great expense. Unless prompt action was taken to repair and refill those tanks which lost their water, much additional loss would be sustained through drying and further deterioration.

The common household tank is erected with its upper edge just under the level of the eaves of the building, the roof of which provides the rain catchment. To meet hydraulic requirements within the house the bottom of the tank is built 6 or 8 feet, and the top 15 feet or more above the ground surface. The tanks contain from 8 (2,000 gallons) to 20 tons (5,000 gallons), or as much as 40 tons (10,000 gallons) of water. They are supported on a base which commonly is little more than 10 or 12 feet in breadth, with their center of gravity 10 or 12 feet above the ground. A 2,000-gallon tank on six footings exerts a load of about 2,700 pounds on each footing, and a 5,000-gallon tank of 12 footings imposes a load of about 3,300 pounds on each. From data gathered during this investigation, many of the tanks having capacities of 10,000 to 25,000 gallons impose loads on individual footings of 4, 5, or as much as 6 tons. Such loads are several times as great as those commonly carried by the columns under an ordinary frame house, and the height of the tank is much greater compared with the breadth of the base than is that of most houses.

The types and adequacy of footings varied greatly. Some footings were solid bedrock. Others were concrete blocks or large flat blocks of rock. Some of the latter were well embedded in the soil, and some were well tied together. Commonly, however, they were not securely embedded and were totally untied, so that under the stresses induced by the earthquake individual footings could turn or shift in relation to each other with comparative ease.

Tanks that are built near the ground require no legs or columns and may have no systematic arrangement of footings under the sills.

In some tanks the bottom planks rest on joists or beams that in turn lie directly on the ground, or on concrete or rock footings having no cross members parallel to the bottom planks. Such an arrangement leaves the bottom of the tank in a precarious position if there is any differential movement of the footings, and poorly protected against even ordinary settling, much less a severe earthquake.

Most of the larger tanks require support at the end of the joists within the circle of the tank chimes, and are supported on a sill or beam pattern that is six- or eight-sided, and the outer columns are six or eight, or more. Usually the columns are braced from near the bottom to the top of adjacent columns, and they may or may not have bracing toward the center of the tank. Most commonly the bracing is spiked or bolted to the outside or inside edges of the columns, so that its effect is offcenter and tends to develop a torque in the columns.

The chief causes of tank destruction during the earthquake were poor footings and inadequate bracing of the supporting structures. It is evident that the footings, although adequate to support the direct static load, commonly were not sufficiently fixed in position or well enough tied to the structure to withstand earthquake. The footing blocks are prone to move during the rocking to which the whole frame is subjected in an earthquake, with progressive yielding and increase of movement to the point where the frame itself fails. A contributing factor undoubtedly was the excessive loads carried on individual footings at some tanks. As already pointed out, some of the larger tanks, as for example, the one at Honaunau School (fig. 44), exerted static loads on each footing of more than 6 tons. Lateral shaking of a mass imposing such loads on individual columns and footings imposed too great a strain on the bracing, and after initial displacement of critical bracing or footings the entire structure quickly collapsed.

There were few eye-witness accounts of the progressive destruction of individual tanks, but it is evident that the interrelated failure of bracing and footings was the chief cause. A few persons heard slopping of water in and from the tanks for an appreciable interval before final collapse. No marked correlation could be shown between the age of the tank and the damage, and only in a few instances was it proven that preexisting impairment was responsible. So many nearly new tanks, in good condition, were destroyed that apparently the stresses developed by general shaking could not be met by the existing bracing. The lateral components were as much as 0.2 or 0.3 of the value of gravity. Likewise the footings became progressively displaced and hastened the destruction. Such stresses are comparable to tilting the tank and understructure to an angle of about 16 degrees and submitting it to repeated vertical loading and unloading. Under such conditions it is not surprising that many of the structures failed.

It is not likely that any feasible methods of construction will entirely eliminate damage from earthquake in the Kona district. The writers believe, however, that marked improvement is possible without incurring an additional expense disproportionate to the value of the tank. Keeping earthquake risk in mind, the important factors are the following:

1. So far as possible, water-storage tanks should be based on the ground on a levelled, preferably concrete, surface. Tanks should not be based wholly or partly on fill unless the entire filled area is enclosed in carefully designed solid retaining walls. These walls should be prepared for unit loads two or three times as great as those from the tank. Lacking such preparation, the tank should be carried on an overall timber crib or mat of adequate size and spacing. Increasing availability of electricity to operate pumps, and commoner use of pressure installations for domestic service should in the future make possible the basing of additional large tanks on the ground.

2. If the understructure consists of sills on columns, the lower ends of the columns should be completely tied together for compression and tension in amounts up to at least half the unit load. For a simple square deck on four columns, the columns should be tied at their feet and each of the four sides diagonally braced from column bottom to top and similarly diagonally braced through the center between opposite columns. So far as possible bracing and cross-tying should be kept in the two planes parallel to the sills and joists respectively, with secondary truncating sills to approximate the form of a circle under large tanks. Without adequate internal bracing in the two rectangular directions, the bracing of a six or eight-sided array of columns around the periphery results in offcenter reactions and may cause structural failure and destruction of the tank.

3. Footings of concrete blocks or large flat stones should be anchored in the ground or to the rock by imbedding them to a depth equal to their area, or by rods and grouting. This method will give bearing resistance against lateral stresses of half the unit vertical load. Concrete piers should be tied to each other unless they are deeply imbedded.

4. Wherever possible all footing-surfaces should be at one level. If this is not possible the long columns should be tied at the level of the footings of the short columns and bracing should be completed at this level.

5. Sills should be fastened at the top by drift pins, and bolts and timber fasteners should be used in the framing of supports for all tanks except the smallest. Braces should be paired or framed into the plane of the columns in order not to introduce torque into the stresses.

6. Frequent inspection, painting or creosoting, and repair of defective conditions will provide longer assurance of reasonable safety, as with any other structures.

DAMAGE TO STONE WALLS

The loose-stone walls characteristic of the Kona area were extensively damaged by the earthquake. The greatest destruction was in the area between Keauhou, 3.5 miles north from Kealakekua, and Pahoehoe, 3 miles south from Hookena (fig. 41). However, isolated instances of wall derangement were observed as far north as Honokahau, 16 miles north of the epicentral area, and Naalehu, 36 miles southeast. The distribution of damage to walls is shown graphically in figure 43. Many miles of wall required rebuilding. As the cost of contract rebuilding is about a dollar a yard, the total monetary loss from the destruction of walls is very appreciable.

At the ancient City of Refuge, at Honaunau, about 20 feet of the seaward side of the main outer wall of the enclosure collapsed. The damage was restricted to a reconstructed part, whereas the remaining parts of the original enclosure wall, and the walls of heiau (temple) platforms, were undamaged. Homer Hayes, who has devoted much study to the City of Refuge, made a highly plausible suggestion concerning the peculiar construction of the ancient walls. He observed that occasional broad slabs extend entirely or largely through the wall, and sometimes bridge open spaces beneath. These slabs are responsible for the greater resistance to earthquakes of the old portions of the wall.

Most of the stone walls consist of irregular fragments of clinkery lava less than a foot across. A few walls have bases of blocks a foot or more long reaching half way through them. In the older ones there are occasional slabs laid partly or entirely through the wall to help tie it together. Because of the rough irregular surfaces of the fragments they can be built nearly vertical, 3 or 4 feet high and about 30 inches thick at the base. Such walls stand well under ordinary conditions, but because of the shortness of the bonding surfaces of adjacent blocks they are rather unstable under any joggling, as by earthquakes. The earthquake of August 21 caused extensive damage. The commonest type of damage was a collapse of the upper part of the downslope face, the fragments rolling down and a short distance away from the base. Such damage was common in north-south walls and near the top. In a few instances those on nearly level ground were dislodged about equally in both directions. However the failure was preponderantly on the western side and the material was displaced westward.

Some of the westward displacement probably resulted from the tendency of the loose material in the wall to lag behind during the initial strong eastward movement of the ground. Greater failure of the western side of the walls was caused by the general westward slope of the ground and because that side was higher and commonly steeper than the eastern. Likewise, there was a tendency for materials to shift downslope under the influence of gravity.

Well-built walls were surprisingly resistant to earthquake damage. Thus the wall along the landward side of the highway from Honaunau to Napoopoo, built of carefully placed rectangular blocks of lava, was almost wholly undamaged despite its proximity to the epicenter. Likewise, in other parts of the epicentral area, older walls in which slabs extending through a large portion of the wall had been used to tie the wall together, showed comparatively little damage.

DAMAGE TO ROADS

Damage to paved roads was of three general types: cracking of pavement, cracking and slumping of shoulders and separation of shoulders from pavement, and collapse of road cuts causing partial obstruction of the road. The latter has already been discussed under the heading "Rock slides." Minor cracking of shoulders occurred over an area extending about 10 miles north and 12 miles south of the approximate epicenter, and a few cracks were formed as far away as ths northeastern side of Kilauea caldera, 47 miles from the epicenter. However, extensive pavement cracking and slumping was restricted to the area between Captain Cook and Hookena. The distribution of cracks in the road is shown in figure 43.

Cracking or slumping of the pavement or shoulders was entirely restricted to portions of the road on fills. Some gullies were crossed by laying a rock fill having a batter, or departure from the vertical, of less than 1 in 4; filling with fine material; and laying asphalt pavement across the top. Such fills were not sufficiently stable to withstand the shaking of a strong earthquake, and in several places the downslope face of the fill was dislodged, allowing the material of the roadbed to settle, thus cracking the pavement. In other places the fill apparently settled a little by compaction during the jostling by the earthquake, causing cracks in the pavement.

A common occurrence was the formation of a crack parallel to the edge of the pavement on its downslope side, either within the pavement a few inches from its edge, or between it and the shoulder (fig. 46). Some of these cracks were as much as 75 feet long and 8 inches wide. This apparently resulted from a downslope lurching of the shoulder that moved as a separate unit from the portion of the fill

FIGURE 46.—Crack along the edge of the highway pavement 2 miles south from Kaimalino, apparently resulting from a downslope lurching of the shoulder, which moved as a separate unit from the part of the fill beneath the pavement.

beneath the pavement. The independence of movement of the shoulder and pavement was interestingly shown along the highway about 2 miles southeast from Captain Cook, where soil and sod on the shoulder was overthrust as much as an inch onto the pavement.

DAMAGE IN CEMETERIES

Many headstones in cemeteries in the area near the epicenter were deranged by the earthquake. As a part of the investigation these cemeteries were examined and a rough statistical study of the damage was made. Unfortunately, owing to shortage of personnel and pressure of other duties, we were delayed several days in making the cemetery examinations, and some restoration of headstones had already taken place. However, in most cemeteries little restoration had been done, and the damage remaining probably was a representative sample of the original damage. The writers believe that even after the stones had been replaced, the derangement could be detected by breaks or scratches or by disturbance of the cement bond at the base of the stone.

There are more than 50 cemeteries in the area, but most are small family or church plots with few graves, and have not been used in recent years. In some cemeteries, burial was in vaults without headstones or the headstones or markers were firmly cemented in place and not readily susceptible to damage by an earthquake of the intensity of the one under study. The most valuable information came from the investigation of a few of the larger cemeteries. Damage at these cemeteries is summarized in table 12, and their locations are shown in figures 41 and 48.

Derangement of headstones included overturning of stones (fig. 47), and shifting of stones on their bases with or without rotation. Many grave caps were broken, some by falling or disturbance of headstones, and some by lurching or slumping of the adjacent subsoil.

FIGURE 47.—Gravestone rotated counterclockwise, in the Daifukuji cemetery at Honalo. Other stones have been thrown from the vacant bases visible in the photograph and are out of sight behind the bases.

Slumping was particularly prevalent on steep slopes where the subsoil is thick and loose. Damage of all sorts was restricted to the area between Honalo and Honokua, 5 miles northeast and 10.5 miles south-southeast of the probable position of the epicenter.

In cemeteries north of Keauhou no damage or derangement was noted. At Lanakila cemetery, 2 miles south from Keauhou, of 15 headstones, 4 were dislodged to the west. Inland and slightly northward, at the Daifukuji Mission in Honalo, about 5 miles north from Napoopoo, of an estimated total of 150 grave markers, 6 toppled west, 7 north, 2 east and none south. Six had been shifted north, 16 were twisted clockwise, and 2 were twisted counterclockwise; 8 grave

caps were broken (fig. 47). It was reported that many more had been disturbed but had been restored.

At Hongwanji Mission cemetery, Kealakekua, which has more than 600 graves, 12 headstones were overthrown to the west, 9 to the east, and none north or south. Thirty-four were twisted right (clockwise), 11 left, one each shifted north, west, and south, and 22 grave caps were broken.

At the Central Kona Church cemetery at Kealakekua, 12 headstones and one large memorial monument were overturned westward, and one eastward. One stone was rotated counterclockwise. In the Christ Church cemetery, just across the highway, 5 headstones were overturned westward, one was rotated counterclockwise, and one clockwise.

At Kahikolu Church, about half a mile south of the Kealakekua fault line, of a total of 10 headstones, 2 were overturned to the west and one was twisted to the right. Two miles farther inland, but only about 0.6 mile south of the fault line, is another cemetery of the Hongwanji Mission. Here, of more than 200 headstones, 29 were still down on September 7, the majority dislodged to the west, and 10 or more had been replaced. Thirteen had been twisted to the right, 4 to the left, and 24 grave caps were broken. There was much damage to caps and markers in the lower section of the cemetery where the ground is composed of rocky talus.

At St. Benedict Church, 1.5 miles farther south, is a cemetery having nearly 100 markers. About half of these are wooden crosses which were not deranged. Several others are light-concrete crosses that have wire reinforcing. Some of these were so broken that the wires were exposed and the markers were supported wholly by one or two of the wires. Of about 20 vertical headstones, 11 were displaced or broken.

The most complete derangement was found in the Kalahiki Japanese cemetery, a small hillside cemetery 3.8 miles south of Kealia, where only 2 markers of 30 were found in position 5 days after the earthquake. The dislodgment was chiefly to the southwest, and to a lesser extent to the northeast. Ten markers were shifted to the north but were not thrown down. Seven, including some of the above, were rotated to the right, and one to the left. Here, on loose steeply sloping ground, many grave caps were broken, owing to poor design and and to being placed on the newly heaped grave mound. This cemetery is about 11 miles south of the probable epicenter. South of this point no cemeteries with headstone susceptible to overturning or rotation were found.

The east-west azimuth of fall of gravestones throughout the area is probably the result of the prevailing westward slope. The orientation of most cemeteries is governed by the general north-south alinement of the principal roads, and in turn most gravestones face the

west or east and the long dimension of their base is oriented north-south. Therefore the stones rock in an east-west direction much more easily than in any other, and the most likely azimuth of fall consequently is an east-west direction. Furthermore, under sustained shaking there is a tendency for all loose objects, including the soil cover, to work downslope to the west under the influence of gravity.

TABLE 12.—*Summary of damage in cemeteries caused by the earthquake in Kona, August 21, 1951*

Name of cemetery	Location	Miles from Napoopoo (and direction)	Approximate number of headstones	Headstones overturned						Headstones rotated	
				Number	Percent	Approximate direction				Clockwise	Counter-clockwise
						N	E	S	W		
Holualoa Japanese	Holualoa	10 N.	300	0	0	0	0	0	0	0	0
Daifukuji	Honalo	5 N.	150	15	10	7	2	0	6	2	16
Lanakila Church	Kainaliu	4.5 N.	12	4	33	0	0	0	4	0	0
Hongwanji Mission	Kealakekua	3 N.	600	21	3.5	0	9	0	12	33	10
Central Kona Church	do	2.5 N.	30	12	40	1	0	0	11	0	1
Christ Church	do	2.5 N.	60	8	13	0	3	0	5	1	1
Kahikolu Church	Napoopoo	.5 S.	10	2	20	0	1	0	1	1	0
Hongwanji Mission	Keei	1.5 SE.	200	40	20	3	22	1	14	13	4
St. Benedict Church	Honaunau	3.5 SE.	100	11	11	0	0	0	11	0	0
Japanese	Kalahiki	7.5 S.	31	20	64	1	6	1	12	14	1

ROTATION OF COLUMNS

Imamura (1937, p. 96) has shown that the direction of rotation of short rectangular columns, such as headstones, can be useful in determining the direction of motion during an earthquake, and consequently the approximate azimuth of the line toward the epicenter. If the earthquake motion is parallel to the sides or to the diagonal (*A–B*, inset figure 48) of the column, rotation probably will not occur. However, if the earthquake motion is in some intermediate direction, such as *E–E′* in figure 48, a rocking of the column will be accompanied by a rotational tendency. A ground motion in the direction *E′* will cause the column to rock on the corner *B*. At the same time, the resultant of the force *E′* in the direction *CD* will tend to rotate the column about the corner *B* in a counterclockwise direction. Similarly a motion in the direction *E* will tend to cause a counterclockwise rotation about corner *A*. In the diagram in the inset, figure 48, directions of earthquake motion in the unshaded octants tend to cause counterclockwise rotation of the column, and directions of motion in the shaded octants tend to cause clockwise rotation.

However this law of rotation can be, and commonly is, upset by other conditions. Inhomogeneity of the terrane may locally cause the principal motion to be in a direction other than the azimuth pointing directly to the epicenter. Also, excentric irregularities in the

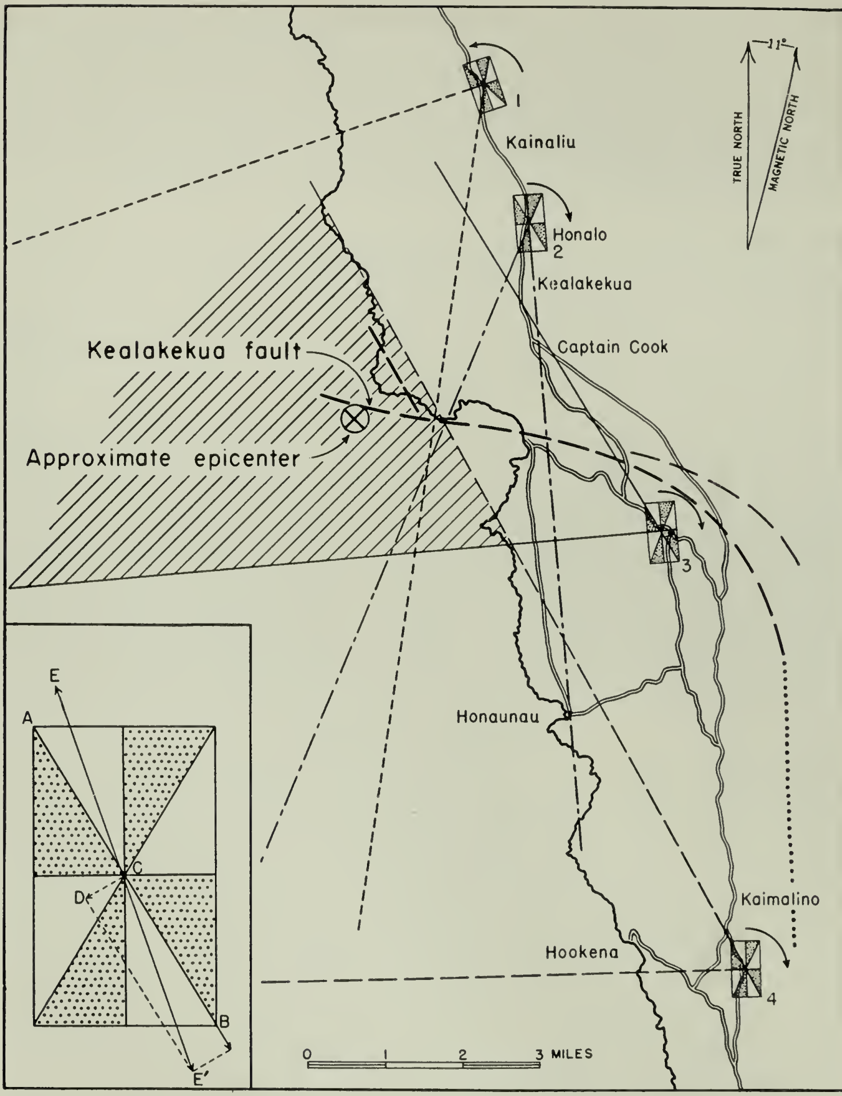

FIGURE 48.—Map of the central Kona area, showing the prevalent direction of rotation of monuments in cemeteries. The cemeteries are indicated on the map by numbers as follows: (1) Daifukuji, Honalo; (2) Hongwanji Mission, Kealakekua; (3) Hongwanji Mission, Keei; (4) Kalahiki Japanese. At each cemetery the arrow indicates the prevalent direction of rotation. The boundaries of the octants containing the direction toward the epicenter are prolonged. The cross-hatched area west of Captain Cook is that in which three or more of the octants overlap. The inset in the lower left is a diagram (after Imamura, 1937) of a horizontal cross section of a rectangular column, indicating the manner in which horizontal earthquake motion (*E–E′*) brings about rotation of the column.

bottom of the monument or its underlying base, or in the adhesion between the monument and its base, may result in rotation around those irregularities independent of the rotation described above.

During our study of the Kona earthquake it soon became evident that to be of value the direction of rotation must be considered on a statistical basis. Thus two columns only 10 feet apart in the Christ Church cemetery at Kealakekua were rotated in approximately equal amounts in opposite directions. However, by using the prevailing direction of rotation of a number of columns in a single area, more useful results were obtained. The average direction of rotation of monuments in each of 6 cemetery areas from 5 miles north to 10 miles south from Napoopoo all were consistent with an origin of the earthquake on or near the Kealakekua fault from 2.5 to 5 miles west from Napoopoo. Cemeteries near the epicenter showed less consistency in the direction of rotation than did those farther away.

In figure 48 is shown the prevalent direction of rotation of monuments in four cemeteries. Four other cemeteries were omitted either because no monuments were rotated or because the number was too small to yield a reliable statistical result. At each of the four cemeteries plotted the boundaries of the octants containing the direction toward the epicenter are prolonged. In an area west of the shoreline, from 2 miles south to 2 miles north of the approximate trace of the Kealakekua fault, three or more of the four significant octants overlap, and it is within this area of overlap that the epicenter should be situated.

LOCATION OF THE EPICENTER

Owing to the dismantling of all but one of the seismographs on the island of Hawaii during the preliminary phase of the earthquake, it is not possible to locate the origin or epicenter instrumentally. The only instrumental datum available is the *S–P* interval of 9.5 seconds given by the Bosch-Omori seismograph at the northeastern rim of Kilauea caldera (fig. 31). Using the travel times given by Byerly (1942, p. 210), this gives us a distance of origin of the earthquake of about 47 miles from the Bosch-Omori instrument. These curves were derived for sedimentary and granitic rocks, but over a period of several years of use at the Hawaiian Volcano Observatory have yielded more satisfactory and reasonable earthquake locations than any others. The use of Jones' (1935, p. 50) curve for duration of the preliminary waves increases the distance only to 49 miles. Taking into consideration the area of greatest intensity of the earthquake, these distances place the origin of the quake 3 to 5 miles west of the coastline in the vicinity of Napoopoo. The depth of origin appears probably to have been between 5 and 10 miles.

Some information bearing on the location of the epicenter can be derived from the study of damage by the earthquake. The general distribution of damage to roads, stone walls, and road cuts along the main highway is shown in figure 43. This is based on a count checked

against odometer mileage, assigning one unit of damage for each 1 to 15 feet of collapsed wall or road cut. Despite irregularities, the graph shows a distinctly symmetrical bell-shaped distribution curve, with its peak about 2.5 miles by road southeast of Captain Cook. An average of more than 60 items of damage per mile in the central 5 miles decreases to only one or two per mile more than 9 miles from the center. This point of maximum damage coincides closely with the position of the buried inland extension of the Kealakekua fault. Other types of damage also were most abundant in the same general area. As most of the aftershocks, located by instrumental means, originated on the Kealakekua fault, it leaves little question that the origin of the major earthquake lay on or near the Kealakekua fault, and that the earthquake almost certainly resulted from movement on that fault.

The greatest structural damage was farther south, at Hookena, where the destruction of the eastern and western walls of the two stone churches suggests an epicenter somewhat farther south. The possibility of a twin earthquake with one epicenter lying offshore nearly west of Hookena has been considered, but no other evidence suggests it, and no signs of a second earthquake could be detected from the seismograms either from the island of Hawaii stations or from the Coast and Geodetic Survey's Barbers Point station on Oahu.

Throughout the Kona area the prevalent direction of fall of rock slides, stone walls and tombstones, was westward, and the next commonest direction was eastward. The seismograms indicate that the first movement of the ground was eastward, and it is probable that some of the westward fall of objects was the result of lagging behind as the ground moved eastward under them. To some extent also, the general east-west azimuth of fall undoubtedly reflects the direction of the epicenter. However, still more important in determining the direction of fall of objects apparently was the prevailing east-west slope. Its effects on various types of damage have already been pointed out.

The prevalent direction of rotation of columns in cemeteries indicates a location of the epicenter within the shaded offshore area in figure 48. This area contains the seaward extension of the Kealakekua fault.

Consideration of all the evidence indicates that the probable epicenter of the earthquake is about 3 miles west of Napoopoo, at latitude, 19°29′ N.; longitude, 155°58′ W.

INTENSITY OF THE EARTHQUAKE

Two methods of determining and expressing the strength of an earthquake are in common use. The older method is based on the observed effects of the earthquake on structures and other objects.

Based on these effects a numerical value is assigned which is termed the "intensity" of the earthquake at any one point. Obviously, since the effects are less at greater distances from the origin of the quake, the intensity decreases away from the epicenter. Various scales of intensity have been proposed. The scale used in the present study is the modified Mercalli intensity scale of 1931 (Wood and Neumann, 1931), in which values range from 1, at which the earthquake is not felt except by a very few persons under especially favorable conditions, to 12 at which damage is total. The second method assigns a value called "magnitude" to the earthquake, based on the effect on standard seismographs at known distances from the origin of the quake (Richter, 1935). The magnitude is a measure of the amount of energy in the earthquake at its point of origin, and consequently should be essentially the same at all measuring stations.

The notice of preliminary determination of epicenter issued by the Coast and Geodetic Survey lists the magnitude of the earthquake of August 21 at 6.75 as determined at Pasadena, and 7.0 as determined at Berkeley, Calif.

Field studies of the effects of the earthquake indicate an intensity of 7 on the modified Mercalli scale in the area near the epicenter, decreasing to 6 at Waiohinu and Naalehu, 5 in the vicinity of Kilauea caldera and in Hilo, and 4 at Honokaa and in the Kohala district at the northern end of the island. At Honolulu, 180 miles (288 km) from the epicenter, the intensity was 2. Populated areas of the island of Hawaii are largely restricted to the periphery of the island. Parts of the interior of the island are almost wholly unpopulated, making it impossible to draw accurate isoseismal lines. Approximate isoseismals are shown in figure 41.

Given a single impulse, the minimum horizontal acceleration that can cause the sliding of a short stone column on a stone base is 71 percent of the value of gravity, decreasing to 57 percent at an angle of emergence of 35° to the horizontal (Imamura, 1937, p. 105). Because the sliding of headstones, and especially base plates, was common in cemeteries during the August 21 earthquake, it might have been concluded that the acceleration during the earthquake was at least six-tenths that of gravity. However, Imamura (1937, p. 106) also has shown that small, short-period vibrations in the epicentral areas of strong earthquakes, although they do not themselves cause the displacement of objects, may so lower the normal values of the coefficients of friction that sliding can be caused by longer period vibrations with accelerations much less than six-tenths that of gravity. The presence of such vibrations in the Kona area is suggested by local vagaries of displacement and other factors. The acceleration which caused the lateral displacement of objects during the Kona earth-

quake is not known, but probably was much less than six-tenths that of gravity.

CONCLUSION

The earthquake of August 21, like most of its aftershocks, probably was caused by movement on the Kealakekua fault. This fault is one of many along which the lower slopes of Mauna Loa and Kilauea volcanoes have moved relatively downward and outward toward the ocean. In this sense the earthquake was tectonic in origin.

Although all earthquakes in Hawaii originate in the volcanoes, the earthquake of August 21 cannot be directly related to any specific volcanic episode. It is possible that it is related in some way to the great extravasation of lava during the 1950 eruption of Mauna Loa, but there is no evidence to demonstrate such a relationship. On September 16 a series of smaller earthquakes originated on the Kaoiki fault system, a series of fractures corresponding to the Kealakekua fault, on the southeastern slope of Mauna Loa. From mid-May until early July abnormally rapid eastward tilting at Kilauea caldera indicated a tumescence of Mauna Loa volcano. There is a possibility that the August 21 earthquake and its aftershocks, and the September 16 earthquakes were caused by a slight upward movement of the central portion of Mauna Loa in relation to the lower slopes. In view of the eruption of Kilauea volcano in June 1952, it appears possible that the numerous earthquakes during 1951 (and early 1952) may have accompanied an inflation of the entire Kilauea–Mauna Loa system.

The southern part of the island of Hawaii is subject to frequent earthquakes, but few are as intense as that of August 21, 1951. The great earthquake of April 2, 1868, judging from the descriptions of damage, was however, much more severe. Wood (1914) assigned to this earthquake (April 2, 1868), an intensity of 10 in the Rossi-Forel scale, which would correspond to an intensity of not less than 10 in the modified Mercalli scale used in this report. Its epicenter was near Waiohinu, in Kau, about 35 miles southeast of that of the Kona earthquake of 1951. Extensive surface faulting took place in the epicentral area. The earthquakes of March 28 and April 3, 1868, also probably were at least as severe as that of August, 1951. The earthquake of October 6, 1929, centered beneath Hualalai volcano, had a magnitude of 6.5 (Gutenberg and Richter, 1949, p. 207), and did damage as far south as Captain Cook. The Maui earthquake on January 23, 1938, had a magnitude of 6.75, about the same as that assigned by the California Institute of Technology Seismological Laboratory in Pasadena for the earthquake of August 21, 1951. The earthquake of May 29, 1950, was assigned a magnitude of 6.25 at Pasadena, and did minor damage in central Kona.

During the years 1929–45 Gutenberg and Richter (1949, table 17) list 8 earthquakes of magnitude 5, or more, that originated in the general Hawaiian area. During the same interval they list 58 earthquakes in California having magnitude of 5 or more, and 127 in Japan and Kamchatka. Thus during those years California had about 7 times as many large earthquakes as did the Hawaiian area, and the Japan-Kamchatka area had about 16 times as many. Based solely on the interval 1929–45, the Hawaiian area can expect an average of about one earthquake of magnitude 5 or more every 2 years.

On the other hand, during the past century, there have been only six earthquakes of intensity comparable to that of the August 21 quake, and no other appears to have been quite as severe in central Kona. There is no assurance that another earthquake equally, or even more severe, will not occur in that area in much less time than a century. It might even occur within the next few months, but judging from the past, that is quite unlikely.

However, like all the rest of the island of Hawaii except the northernmost part, Kona experiences lesser earthquakes frequently. Well-built structures, with footing of better quality than many of those found in Kona now, will minimize and may eliminate the damage resulting from such ordinary earthquakes.

It may not be economically feasible to build in such a way as to eliminate damage from the infrequent large earthquakes.

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